Barwon Downs Monitoring Program

BARWON WATER

Review of Conceptual Model at Numerical Model Boundaries

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Project manager:	Stephen Parsons
Author:	Stephen Parsons, Mike Dudding
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Jacobs Group (Australia) Pty Limited
ABN 37 001 024 095
Floor 11, 452 Flinders Street
Melbourne VIC 3000
PO Box 312, Flinders Lane
T +61 3 8668 3000
F +61 3 8668 3001
www.jacobs.com

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Purpose

Barwon Water commissioned experts from Jacobs-SKM to identify any limitations in current understandings on the hydrogeology of the Barwon Downs groundwater model. The concern was not a lack of field data, but whether all available data was being used to ensure that current conceptions were as sound as possible.

This report focuses on how model boundaries to the south-west (Gellibrand) and the north (Birregurra) are currently set up, and whether recommendations can be made to improve the model. Improving accuracy of the model boundaries by using the latest geographical and geological information improves the ability to predict a broad range of future scenarios any possible impacts and prepare management strategies ahead of the borefield licence renewal in 2019.

Background

The Barwon Downs borefield is operated under licence from Southern Rural Water. This licence was granted in 2004 and is due for renewal in June, 2019.

The borefield provides a reliable supply source during drought for the regional communities of Geelong, Surf Coast, Bellarine Peninsula and parts of Golden Plains. During the worst drought on record (2006-10), the borefield provided up to 70 per cent of Geelong's drinking water.

Barwon Water undertakes a monitoring program for the Barwon Downs borefield in accordance with licence conditions and currently monitors:

- Groundwater levels,
- Groundwater salinity,
- Subsidence,
- Flows in Boundary Creek and the Barwon River,
- Vegetation health, and
- Volumes of water extraction.

While this program was good practice at the time of the last licence renewal, there has been increasing community interest in potential environmental impacts related to pumping from the borefield.

Expanded monitoring program

Barwon Water has committed to expanding the existing monitoring program to address community concerns and increase understanding of any local impacts from groundwater pumping.

The new monitoring program includes:

- 36 new groundwater monitoring bores to better understand both the regional groundwater system as well as any localised pockets of groundwater closer to the surface,

- 14 new vegetation monitoring sites to better understand if vegetation in the catchment is dependent on groundwater for hydration, and whether pumping the borefield lowers the watertable enough that vegetation can no longer access groundwater through roots,
- four new areas that may be affected by potential acid sulphate soils, and whether pumping the borefield lowers the watertable enough that acid is eventually released, and
- studying the ecology in Boundary Creek to identify high value flora and fauna, and combine this with four new stream gauges to decide what environmental water flow requirements are needed to sustain ecological values.

The new program will inform the licence renewal process by making recommendations on how to best manage the groundwater resource, aiming to balance the needs of the environment and local community, alongside the drought insurance policy of a regional city.

Why is a groundwater computer model needed?

The simulation of groundwater systems using computer models is standard practice. Models are used for various purposes including education, investigations and water resource management.

In general terms, a model is a simplified representation of a real groundwater system that uses mathematical equations solved by a computer program. The new monitoring program will increase understanding of the Barwon Downs groundwater system in its normal state. This will improve spatial complexity and physical processes (such as groundwater flow and connectivity between geological layers) captured in the model.

<u>Why is this important?</u>

Understanding the system's normal state underpins the model's accuracy in predicting how the groundwater system will respond to different stressors such as climate change, drought, changes in land use practices and groundwater extraction. Results from the modelling can then be combined with other science to identify and manage any potential impacts that may occur as a consequence of stress.

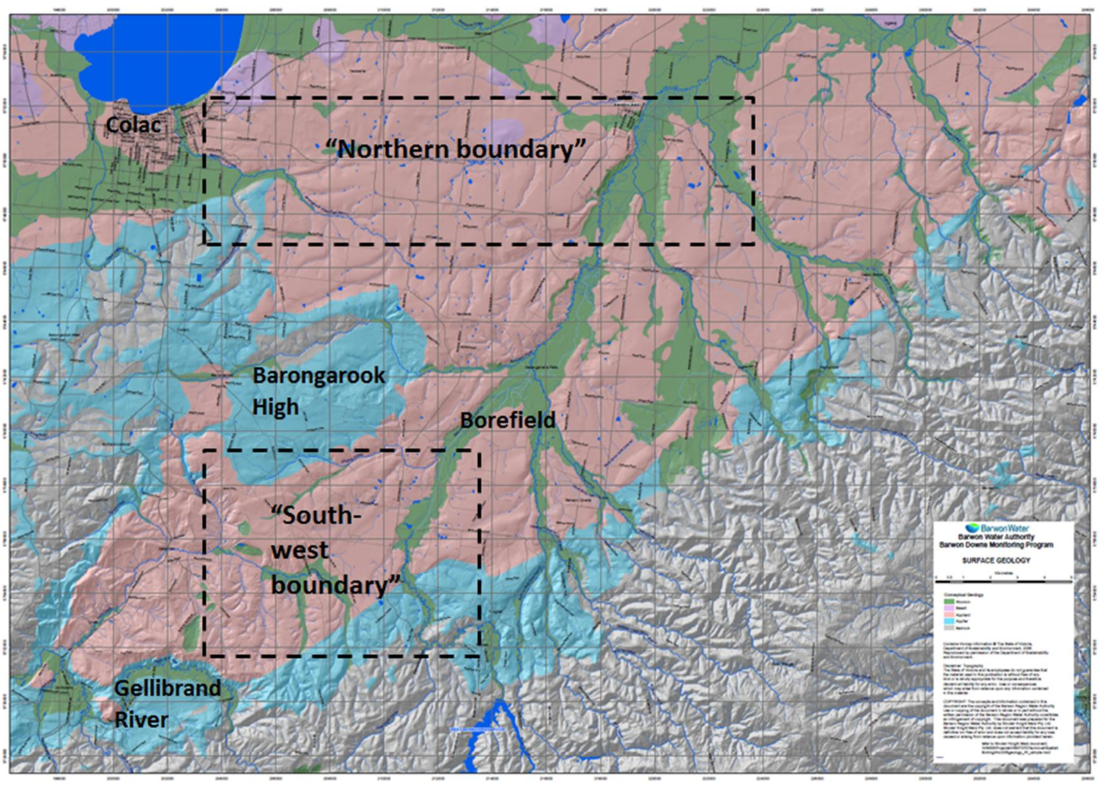
Findings

Boundaries are one of the important areas in a groundwater model. These may be physical boundaries to groundwater flow, or boundaries that represent the extent of the computer model. Boundaries can influence the extent of drawdown caused by groundwater pumping and control how the model allows water into or out of the system.

This study focused on boundaries in the following two areas (refer to Figure E-1):

- South west boundary – the area between the Barwon Downs and Gellibrand groundwater sub-basins, and
- Northern boundary – Birregurra and Colac faults, and postulated Barongarook Creek Fault.

Figure E-1 Areas of focus in the conceptual model review (blue indicates outcropping aquifer, pink outcropping aquitard, green shows alluvial sediments and grey represents outcropping bedrock)



The south-west boundary

The definition of the south-west boundary influences the extent to which potential impacts from groundwater pumping may extend into the Gellibrand catchment. This is an important part of the model because:

- There are significant groundwater receptors in this area, such as the Gellibrand River and local springs, and
- The computer model does not match well with observed groundwater behaviour.

The northern boundary

While there are few significant groundwater receptors (immediately) beyond the northern boundary of the model, it is important that this part of the groundwater system is well defined so the model allows accurate volumes of groundwater to flow into and out of the model across this boundary.

Review of aquifer thickness and extent

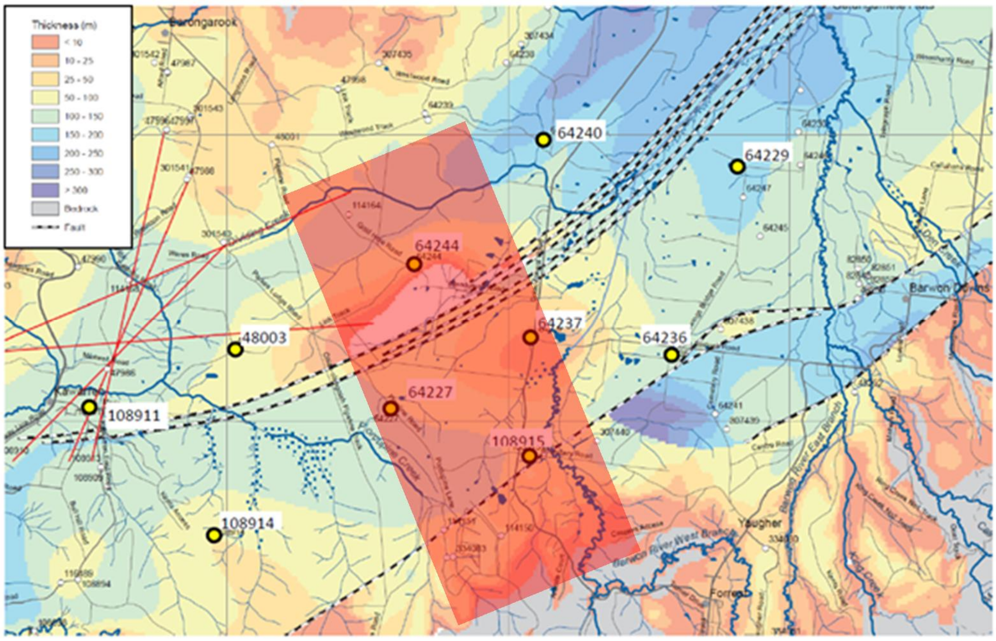
The review involved assessing how well the geology and topography in the current Barwon Downs computer model matched available information. Improving computer model layers by reconstructing the thickness and extent of underground rock formations will improve understanding of any impacts to the water table, as well as the possibility of activating acid sulphate soils. Comparisons were made with a more recently developed computer model for the Newlingrook area. This found the Newlingrook model was a better match and a logical starting place to rebuild the computer model layers.

Identifying the groundwater divide

A comparison of pre-pumping (1987) groundwater levels and post-pumping (2012 and 2014) groundwater levels indicated:

- in the pre-pumping condition, the location of the groundwater divide between the Barwon and Gellibrand groundwater catchments does not match the surface water catchment divide,
- the groundwater divide shifted during pumping, which is considered normal. Groundwater divides are not fixed like surface water catchment divides, and move naturally due to seasonal changes or long term recharge rates, and
- there is a barrier which restricts groundwater flow between the Barwon and Gellibrand catchments. This means pumping from the Barwon Downs borefield will have minimal to no impact on flows in the Gellibrand River.

Figure E-4 – Approximate location of hydraulic barrier inferred from the drawdown analysis



Need for additional monitoring assets

This review concluded additional stream gauges for the upper Gellibrand catchment are not required as drawdown in both the aquitard watertable and aquifer watertable is predicted to be less than 50 cm and less than one metre over the long term, respectively.

This review advises against the need for further monitoring bores for the Barwon Downs Monitoring Program.

Recommendations

This study recommends:

1. The geological layers for the south-west and the north-east corners of the current computer model need to be amended using the Newlingrook model as a starting point,

2. The boundaries of the current computer model need to be expanded (as far as Gellibrand in the south-west corner) to include bore 56055 in the north-west corner and by up to 3 km in the north-east corner, and

3. The representation of the Colac-Birregurra Fault in the computer model should be reviewed and a more suitable boundary (rather than the existing no-flow boundary condition) used to allow for groundwater flow across the fault.

Secondary recommendations include:

1. Further surveys of monitoring bores in the south-west area to understand causes of lower than expected drawdown,

2. Obtaining groundwater level data from private bores on the north side of the Colac-Birregurra fault to add to the reconstructed model,

3. Investigating causes of drawdown in bores around Kawarren to estimate the likely magnitude of groundwater pumping in the area,

4. Utilise the drawdown analysis method to examine the nature of the Bambra fault boundary (the southern and south-east boundary of the computer model), and

5. Monitor a pair of nested bores on either side of the Bambra fault to support the analysis of the Bambra fault boundary (the southern and south-east boundaries).

Contents

Executive Summary

Background

The Barwon Downs borefield is used to extract groundwater when other sources, like Geelong's reservoirs, begin to run low during drought. It therefore forms a key part of the future water security for Geelong and surrounds. Use of this groundwater is licenced by Southern Rural Water, which manages all groundwater in southern Victoria. To improve understanding groundwater in this area and better manage the use of the Barwon Downs borefield, Barwon Water currently monitors:

- Groundwater levels
- Groundwater salinity
- Subsidence
- Flows in Boundary Creek and the Barwon River
- Vegetation health, and
- Volumes of water extraction

Barwon Water is in the process of implementing an expanded monitoring program, in order to improve understanding of potential impacts of groundwater extraction in the catchment and how best to manage the groundwater resource. This information will also be used to inform the groundwater licence renewal process in 2019.

The new monitoring program includes installation of additional groundwater observation bores, establishment of new vegetation monitoring sites, monitoring of sites potentially affected by acid sulphate soils, a study of ecology and environmental water flow requirements in Boundary Creek and installation of new stream gauges (and re-activation of some old stream gauges) in Boundary Creek.

Purpose of this study

Some of the knowledge gaps being filled by the updated Barwon Downs monitoring program seek to address physical gaps in the program (e.g. new bores or stream gauges provide levels or flow at a particular location). However there is a different type of knowledge gap relating to how the system behaves overall. Firstly in the 'historical' state and then under various new changes (e.g. drought, land use change, groundwater pumping etc). In other words, lots of data can be collected but unless it is interpreted and incorporated in a way that it builds on the existing understanding of the groundwater system, then the data on its own may be of limited use.

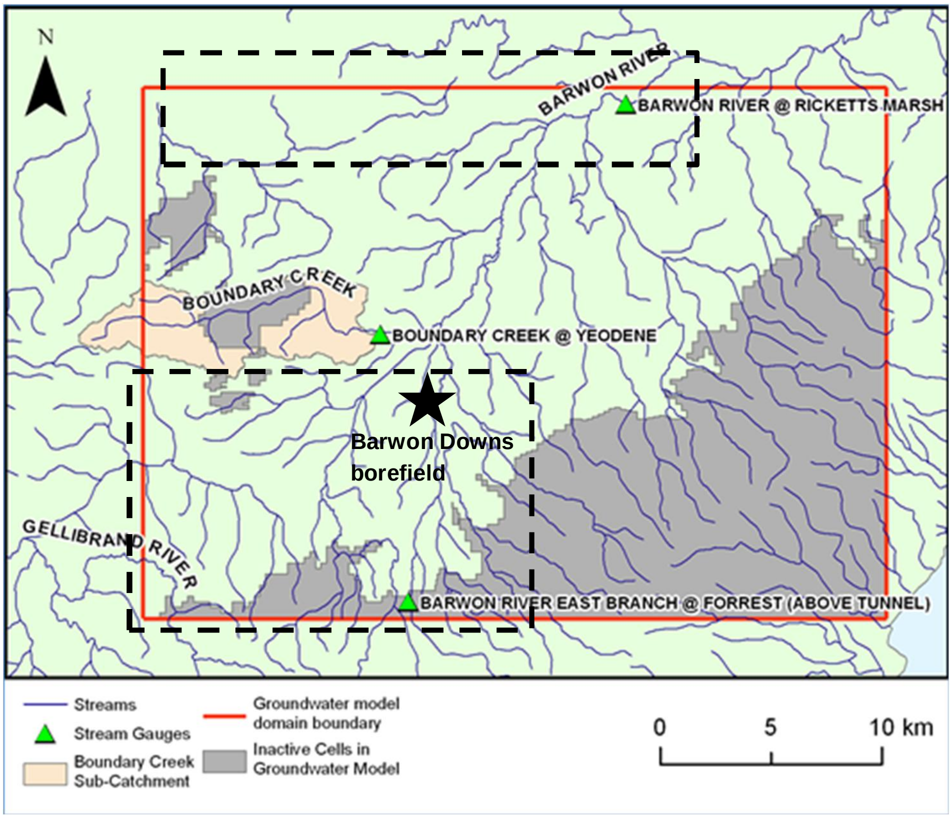
Hydrogeologists refer to this 'big picture' as the "*conceptual model*" of the groundwater system. New data can either confirm the existing conceptual model, or it can add new understanding/complexity or it can change the existing model (i.e. where prior understanding is seen as unsuitable). A conceptual model becomes the common understanding on which predictive tools are based to estimate changes to the groundwater system. These tools can range from simple groundwater flow equations up to complex numerical models (run using computers) which capture much of the spatial complexity and processes of the physical system, and mathematically simulate groundwater levels and flow. The conceptual model is important in ensuring the computer model (also referred to as a numerical model) is useful in indicating how the groundwater system will respond to changes such as groundwater extraction. (It is important to note that these findings do not mean that previous versions of the computer (numerical) model were not 'correct', only that improvements will narrow the range of uncertainty in some new areas of interest). From a licence renewal perspective, computer model results can be combined with other scientific information to identify whether any significant environmental risks exist.

One of the important areas in a groundwater conceptual model is at the boundaries of the model – the boundaries may be physical boundaries to groundwater flow, or they may be boundaries that represent the extent of the computer model. Boundaries are important because they can potentially control the extent of drawdown caused by groundwater pumping and they also control how the model allows water into or out of the system, which can significantly affect the behaviour of the computer model.

One of the recommendations of an early review of data gaps in the Barwon Downs program was to use existing data to evaluate whether the aquifer around the current numerical model boundaries is sufficiently well defined in the following two areas (also shown in Figure E-1):

- South west boundary – the area between the Barwon Downs and Gellibrand groundwater sub-basins, and
- Northern boundary – Birregurra and Colac faults, and postulated Barongarook Creek Fault

Figure E-1 Areas of focus in the conceptual model review - the red line shows the boundary of the current numerical model and black dashed lines show the two areas of primary interest in this review



The south west boundary is important because the definition of this area will influence the extent to which potential impacts from the groundwater pumping extend into the Gellibrand catchment. This is an important part of the model because there are important groundwater receptors in this area (e.g. Gellibrand River, springs) and further the current computer model does not calibrate well in this area (this means that the computer model results do not match well with the observed groundwater behaviour in this part of the model). While there are not many significant groundwater receptors (immediately) beyond the northern boundary of the model, it is important that this part of the groundwater system is well defined so that the computer model will allow the right volumes of groundwater to flow into and out of the model across this boundary.

In summary, the purpose of this review was to examine the available existing data in these two areas to see if there were any significant limitations in the hydrogeological conceptual understanding of these two areas. The main concern was not a lack of field data in the area, but that all available data was being used to ensure the conceptualisation was as sound as possible.

Findings

1. Review of aquifer thickness and extent

The review involved assessing how well the geology in the current computer model matches available information. A comparison with a different and more recently developed computer model (the Newlingrook model) was a key part of this assessment. The study found that the Newlingrook model better matches the geology than the current computer model and is a logical starting place in reconstructing the computer model layers.

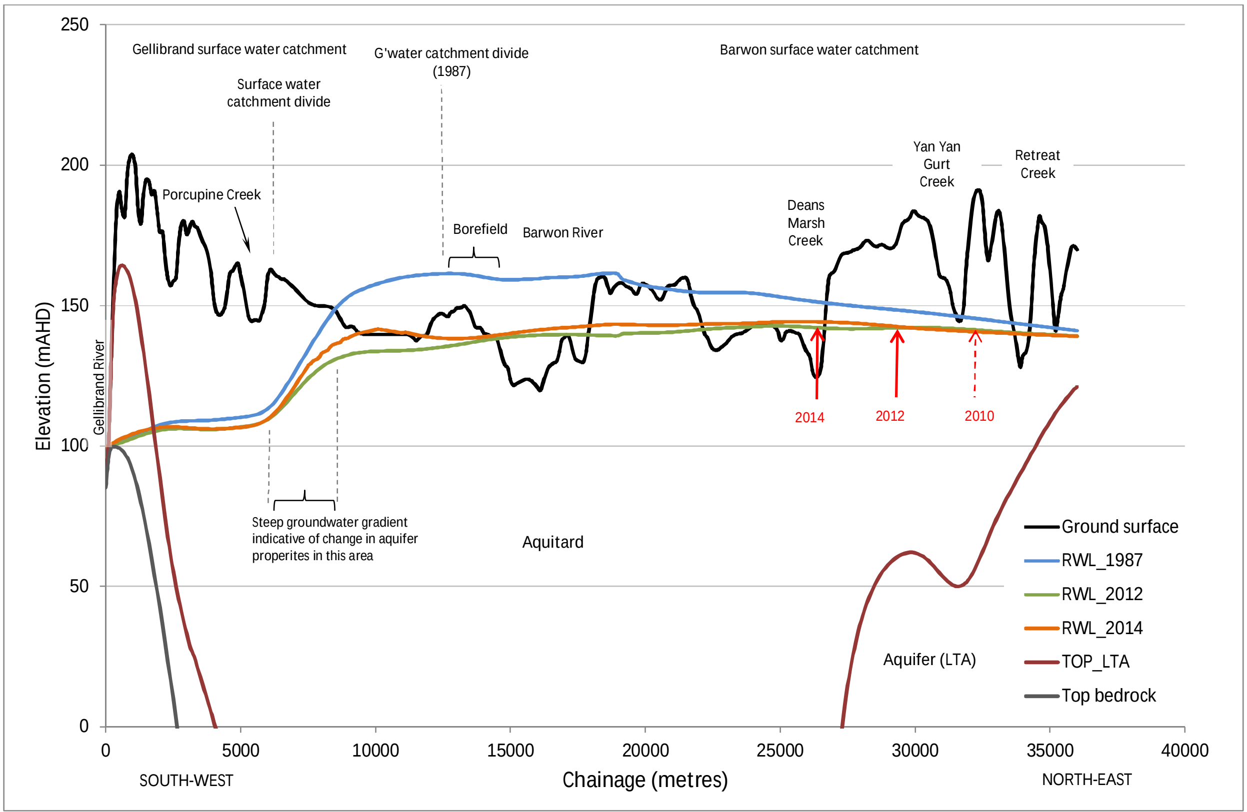
In the north east corner of the model there is a significant difference between the Newlingrook model and the current computer model layers. The Newlingrook model suggests that the aquifer from which the borefield extracts water is deeper than used in the current computer model. The implication is that the risk of lowering the watertable (and associated risks such as activation of potential acid sulphate soils) is likely to be significantly overstated by the current computer model in the Deans Marsh-Bambra area.

2. Review of aquifer potentiometry

A comparison of pre-pumping (1987) groundwater levels and post-pumping (2012 and 2014) groundwater levels was undertaken. The review indicated that:

- In the natural (pre-pumping) condition, the location of the groundwater divide between the Barwon and Gellibrand groundwater catchments is not coincident with the surface water divide but is located within the Barwon surface water catchment.
- Groundwater divides (in the confined part of the aquifer) migrate under pumping, but this is a normal aspect of any groundwater pumping, and in itself is not a good indicator of potential impacts of groundwater pumping. Groundwater divides are not like surface water catchment divides and move naturally due to changes in recharge rates.
- The relatively steep slope of the groundwater level surface between the Barwon and Gellibrand catchments is an indicator of some form of barrier or restriction to groundwater flow in this area.
- Under the effect of pumping, the drawdown (reduction in groundwater level due to pumping) spreads much further in a north-east direction and significantly less so to the south-west, i.e. towards the Gellibrand catchment. This also suggests that there is some type of hydraulic barrier in this direction.
- Groundwater gradients towards the Gellibrand River are essentially unchanged, meaning that any potential change in groundwater contribution to the Gellibrand River is likely to be very small.

Figure E-2 Section along the Barwon Downs Graben showing groundwater levels at different dates



3. Drawdown analysis

The response of groundwater levels in observations bores between the bore field and the model boundary in the south west (towards and into the Gellibrand catchment) were reviewed to understand how the aquifer behaves in this area. The observation bores in this area fall into two categories – rapid response bores which respond quickly to pumping and have relatively large drawdown, and subdued response bores which respond more slowly to pumping and have a relatively small drawdown. The two categories of bores can be seen clearly in Figure E-3. Analysis of drawdown in these bores indicates that there is some form of barrier to groundwater flow between the Barwon Downs and Gellibrand groundwater sub-basins (approximately located as shown in Figure E-3). The analysis further shows that the aquifer is not uniform in its properties, and is likely to comprise multiple zones of varying permeability and storage. Permeability is likely to be highest near the borefield and lowest in an area around bores 64237 and 64244 but are likely to be highly variable in size and location (i.e. not necessarily as shown in Figure E-4). The analysis in this assessment provides a strong basis on which the conceptual model (and ultimately computer model) should be refined.

Figure E-3 – Bores analysed in drawdown analysis. ('Rapid response' bores are 64229, 64236, 64237 and 64240. The remainder are 'subdued response' bores)

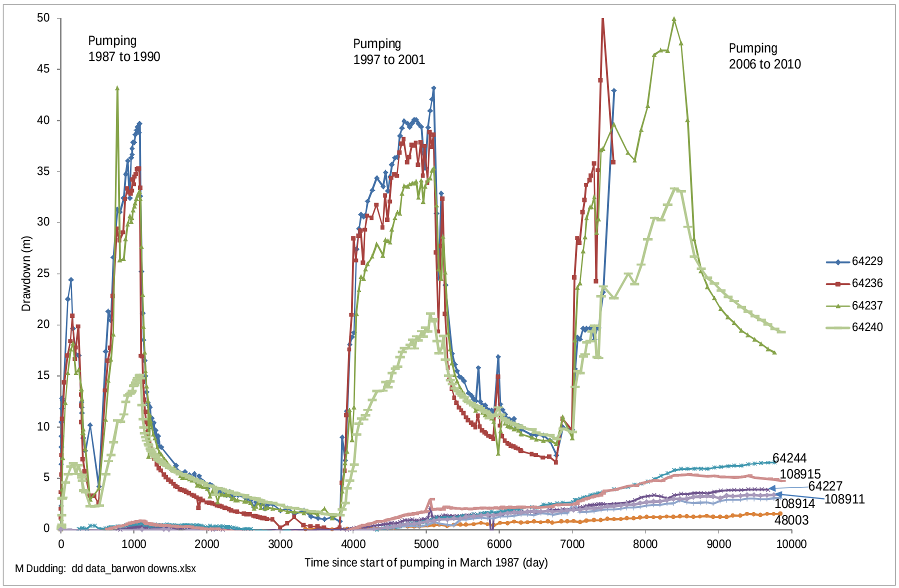
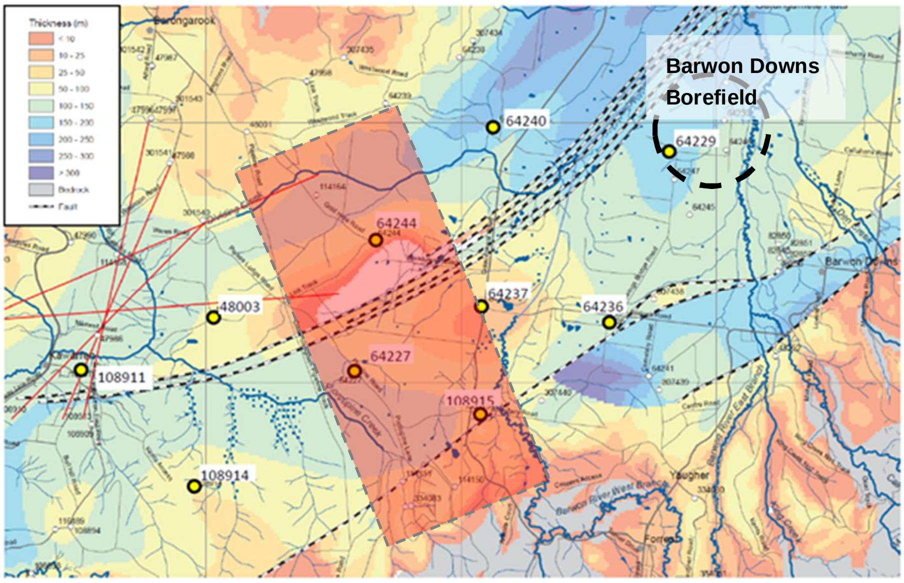


Figure E-4 – Approximate location of hydraulic barrier inferred from the drawdown analysis



4. Review of need for additional gauges in the upper Gellibrand catchment

The primary purpose of this review was not to predict potential impacts of Barwon Downs pumping in the Gellibrand catchment. However, part of the study involved recommending whether additional stream gauges were required in the upper Gellibrand catchment area. The results described above suggest that any impact on the Gellibrand system will be small due to the effect of the hydraulic barrier in the south west area. To address this issue further, a predictive assessment of drawdown was undertaken. The results indicate an estimated drawdown in the aquitard of less than 50cm over the long term. Based on this result and on other findings of this report, drawdown in the aquitard watertable in the Gellibrand Catchment (in particular Porcupine Creek) is likely to be small to negligible and hence installation of additional stream gauges in this area is not recommended.

The potential for impacts where the aquifer outcrops in the Gellibrand catchment, in particular Ten Mile Creek and Yahoo Creek, was also considered. Drawdown mapping indicates that drawdown in these areas in 2012 (a time period of approximate maximum historical impact from the borefield) is less than 1 metre. In Jacob's opinion the likelihood of any significant impacts on streamflow is considered to be low for these creeks. As such, installation of additional stream gauges for these creeks is not recommended. Ten Mile Creek has some periods of historical flow record which will be useful data during model calibration. Further, a new shallow observation bore was recently installed adjacent to Ten Mile Creek, so there is local monitoring infrastructure in place.

A more detailed analysis of potential impacts on creeks in the Gellibrand catchment will be undertaken using the re-calibrated numerical model, and this current review does not preclude installation of stream gauges at some stage in the future.

5. Summary against project objectives

The purpose of this review was to ensure that any limitations in the hydrogeological conceptual understanding of the two areas (south-west and northern boundary) were identified, and that recommendations to address these limitations were made. Findings for the key objectives of this study are summarised below:

1) *Identify the potential for the south west area to act as a barrier or partial barrier (i.e. restriction) to groundwater flow between the Barwon Downs and Gellibrand groundwater sub basins* – There is some form of barrier to groundwater flow between the Barwon Downs and Gellibrand groundwater sub-basins, and the barrier is likely to comprise a low permeability zone or zones in the confined aquifer, and areas of high storage co-efficient (capacity to store groundwater) and/or an area with high leakage rates from the aquitard.
2) *Identify the potential for the Birregurra and Colac Faults to act as a barrier to north-south groundwater flow* - The Colac-Birregurra Fault is unlikely to act as a no flow boundary as is employed in the current computer model. However, it is likely that there is a significant reduction in permeability across the fault.
3) *Identify any unusual or unexplained characteristics that may require further investigation*
    a) The cause of the low permeability in the subdued response bores (bores with relatively low drawdown due to pumping) is not well understood and should be further investigated
    b) Investigation and understanding of the bores with relatively low response to drawdown should also consider revising the computer model layers so that lithology (i.e. what the material is made of, e.g. sand, clay, sandstone etc) is used to define layers in the aquifer, rather than the current basis which uses stratigraphy (i.e. layers that are defined based on the age of the material).
    c) The revised interpretation in the NE part of the model – with the aquifer being significantly deeper than in the current computer model - should be confirmed, given the implications for watertable drawdown in this area
    d) The cause/s of drawdown in the bores around Kawarren should be investigated further
4) *Identify alternative bore locations and/or depths of proposed drilling program (if any)* – No new bores are recommended from this program.
5) *Compare review outcomes against current groundwater (computer) model and identify changes that may be required to ensure the model adequately represents the conceptual model:*
    a) The aquifer structure in the south-west corner of the model needs to be amended, using the Newlingrook model as a starting point
    b) The aquifer structure in the north-east corner of the model needs to be revised, using the Newlingrook model as a starting point
    c) The no-flow boundary condition imposed on the Colac-Birregurra fault should be removed, and replaced with a boundary that represents a significant reduction in hydraulic connection (e.g. large reduction in permeability across the fault).

d) The numerical model boundaries need to be expanded, approximately as far as Gellibrand in the south-west corner, to include bore 56055 in the north-west corner and by at least 2-3 km in the north-east corner.

Limitations/exclusions of the study

The purpose of the study was not to determine the magnitude of impacts of the Barwon Downs borefield on the Gellibrand groundwater system. Commentary and estimation of such impacts have been made in this report, as a means to assessing the need for further monitoring infrastructure in these areas. While these assessments indicate that any noticeable impacts are unlikely, a more detailed assessment of these impacts will be made once the computer model has been updated and recalibrated.

Recommendations

This report recommends that:

1. The geological layers within the current computer model need to be refined, using the Newlingrook model as a starting point.
2. Refinement of the conceptual model (where the computer model does not match well with the observed data) should be undertaken before the computer model is built.
3. The boundaries of the current computer model need to be expanded.
4. The way the Colac-Birregurra Fault is represented in the computer model should be reviewed and a more appropriate boundary employed that allows for groundwater flow across the fault.
5. The cause of the low permeability in the bores with lower than expected drawdown (in the south west corner of the model) should be further investigated. To this end, gamma logging (a tool lowered into bores which records clay content of the formation) of key bores in this area is recommended.
6. Attempts to obtain groundwater level data from some private bores on the north side of the Colac-Birregurra fault should be made, and if available analysed using methods similar to those applied in this assessment.
7. The cause/s of drawdown in the bores around Kawarren be investigated further, including estimating the likely magnitude of groundwater pumping in the area.
8. The drawdown analysis method be employed to examine the nature of the Bambra fault boundary (the southern and south-east boundary of the computer model).
9. Related to the above recommendation, a review of paired bores (bores in close proximity to each other) on either side of the Bambra fault should be conducted and the value of installing data loggers in some of these bores be assessed.

Further details on these recommendations are contained in the body of this report.

Important note about your report

The sole purpose of this report and the associated services performed by Jacobs is to review the hydrogeological conceptual model in the south west corner and northern boundary of the current Barwon Downs numerical model, in accordance with the scope of services set out in the contract between Jacobs and the Client. That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

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1. Introduction

The Barwon Downs bore field is operated under licence from Southern Rural Water. This licence was granted in 2004 after an extensive review process involving an expert advisory panel which considered potential impacts and conditions required for the new licence. This licence is due to expire in June 2019.

The Barwon Downs licence renewal process comprises four stages, with Stage 1 currently in progress. Part of Stage 1 included a desk top study which identified potential gaps in the hydrogeological conceptual model and made recommendations on how these gaps should be addressed. One of the recommendations was to use existing data to evaluate whether the aquifer around the current numerical model boundaries is sufficiently well defined in the following two areas:

- South west boundary – the area between the Barwon Downs and Gellibrand groundwater sub-basins, and
- Northern boundary – Birregurra and Colac faults, and postulated Barongarook Creek Fault

Although it was considered unnecessary to undertake site investigations in these areas, it was considered prudent that a desk based data review be conducted in a timeframe that would enable any significant gaps/issues identified in the review to be incorporated into a field program, if required, well before licence renewal.

1.1 Objectives

The overarching objective of this review is to ensure that any limitations in the hydrogeological conceptual understanding of these two areas are identified, and that recommendations to address these limitations are made. This is to ensure that when the numerical model is used to simulate various scenarios of borefield operation and estimate potential impacts, that the outputs of the model are not limited by poor conceptualisation in these two areas. The sub-objectives of this study are summarised as follows:

1) Identify the potential for the south west area to act as a barrier or partial barrier (i.e. restriction) to groundwater flow between the Barwon Downs and Gellibrand groundwater sub basins
2) Identify the potential for the Birregurra and Colac Faults to act as a barrier to north-south groundwater flow
3) Identify any unusual or unexplained characteristics that may require further investigation (and/or modification to the drilling program)
4) Identify alternative bore locations and/or depths of proposed drilling program (if any)
5) Compare review outcomes against current groundwater model and identify changes that may be required to ensure the model adequately represents the conceptual model (note this is a first step in the refinement of the conceptual model, because more data will be obtained at a later date from Stage 2, and during re-calibration of the refined groundwater model in Stage 3).

1.2 Key assumptions and data sources

This review has only examined existing data and used analytical tools (i.e. no numerical modelling has been undertaken).

As well as the existing data compiled for previous projects at the site, the following data has been collected and compiled from the following sources:

- GeoVic 3 – coal exploration bore data (locations, depth, lithology and geophysical logs)
- The GEDIS database – currently known bores (locations, depth, lithology and geophysical logs)
- Victorian Stratigraphic database (lithological and stratigraphic logs)
- Hard copy reports (geophysical logs)
- The current Barwon Downs numerical model and the Newlingrook model (model extents and layers)

- Groundwater Management System and Visualising Victoria's Groundwater data warehouse (groundwater level and construction information)

1.3 Key tasks

As well as data collection and compilation, the following tasks have been undertaken to refine the conceptual model:

- An assessment of the aquifer thickness and extent in the south west area and north east area involving:
    - Review of the surface elevation of the bedrock and Lower Tertiary Aquifer within the two numerical models
    - Review lithological and geophysical logs and compare to the surface elevations of aquifer and bedrock in the models
    - Estimation of the likely aquifer conductivity range from lithological data
    - Comparison of the surface elevations (and therefore thickness), unsaturated zones and hydraulic conductivity with the current (Barwon Downs) groundwater model
    - In addition, the project has involved development and review of potentiometric surface maps for three different dates to assess whether the groundwater divide between the Barwon and Gellibrand catchments has moved pre and post pumping
- The use of pumping test analysis methods to identify the aquifer model (e.g. leaky, bounded) that best fits the drawdown data

2. Aquifer thickness and extent

Barriers or restrictions to groundwater flow can be caused by the thinning of an aquifer, the aquifer being unsaturated or by the presence of low hydraulic conductivity material. To evaluate whether model boundaries adequately reflect the hydrogeology in the southwest and northern areas, an assessment of the aquifer thickness, aquifer saturation and permeability has been undertaken.

A review of the aquifer structure in the two areas of interest in the current Barwon Downs numerical model has been undertaken via comparison with:

- Maps and associated structure contours prepared for the Newlingrook project. (The 'Newlingrook project' refers to a hydrogeological investigation commissioned by Barwon Water and conducted by SKM during the period 2007 to 2010 in the Kawarren and Gellibrand area. Amongst other tasks, the project involved drilling and testing of new bores in the area and developing new hydrostratigraphic layers for the wider Newlingrook area. These layers were prepared for a numerical model which was constructed (although never run and calibrated), as the project was terminated prior to full completion of all tasks. The study area for the 'Newlingrook project' encompasses the area of the current Barwon Downs numerical model).
- Other maps, such as the Colac 1:50,000 Geology Map and those presented in Witebsky (1995)
- Bore data and in particular lithological and geophysical log information

  In the proposal it was also suggested that this review would involve comparison with maps prepared for the Southern Rural Water (SRW) hydrogeological southern Victoria mapping project. However, upon further consideration, this task has not been undertaken because the scale of the SRW mapping is not suitable for this project i.e. the resolution is much coarser and hence will not contain the features relevant to the scale of interest in a numerical model, e.g. it does not contain the monocline within the Graben. Further, many of the layers of interest are not contained in the SRW mapping, e.g. the Mepunga, Pember Mudstone and Pebble Point formations are not differentiated within the LTA.

2.1 Review of the elevation and thickness of Lower Tertiary Aquifer and bedrock

Figure 2.1 shows the difference in thickness of the Lower Tertiary Aquifer between the current Barwon Downs Model and the Newlingrook Model. Figure 2.2 and Figure 2.3 presents two additional figures which show the differences in the top of the Lower Tertiary Aquifer and top of basement respectively, between the current Barwon Downs Model and the Newlingrook Model.

Figure 2.1 shows that there are significant parts of the current numerical model domain where there are very large discrepancies between the current model and the Newlingrook model, including significant areas of differences greater than 100%. While the figure is useful for highlighting differences between the two models, it does not indicate which of the two models is likely to better represent reality. In order to assess which model is more likely to be accurate in different parts of the study area, the model layers have been compared to the available stratigraphic information at the south western and northern boundaries. Figure 2.1 also shows bore sites which are of relevance to such a review. Bores are only shown in this figure if they have a stratigraphical interpretation and secondly, they penetrate through the full LTA thickness (note that there is a much larger number of bores in the area with stratigraphic information, but they do not penetrate the entire sequence – these bore sites will be of relevance to rebuilding or reconstructing model layers).

Available stratigraphic information was based on an interrogation of the "Victorian Stratigraphic Database" (SKM, 2010; Prepared for the Department of Environment and Primary Industries). (This stratigraphic database was initially undertaken as part of an aquifer mapping project of Southern Victoria for SRW; SKM and GHD 2009). The database now contains over 208,000 registered groundwater, mining and petroleum exploration holes principally from DSE's GMS database and DPI's GEDIS database plus over 105,000 boreholes with raw drillers' and/or geologists' logs and over 21,000 boreholes with interpreted logs). The black dots in Appendix A contains a figure showing all bores with stratigraphic information within the study area that appear to have not been used in either development of the Newlingrook model or the current numerical model. These should be used in future development of any stratigraphic surfaces for the Barwon Downs area.

The comparison between the Newlingrook model and the current numerical model is presented in Table 2.1 for the south-west area and in Table 2.2 for the northern area. These tables present the sites ranked in order of the greatest to least discrepancy, up to a maximum difference of difference of 20% in LTA thickness between the models. While the ranking presented within the table is based on differences in LTA thickness, the table also includes comparison with the top of LTA and the top of bedrock. The shaded cells in the table indicate the model which most closely fits the available stratigraphic information.

2.1.1 South-western area

The following comments are made regarding comparisons between the two model layers and the available stratigraphic information for the south west area:

Aquifer (LTA) thickness

In terms of LTA thickness, the Newlingrook model most closely represents the available stratigraphic information in the south western area. At 27 of the 33 bores in Table 2.1 the Newlingrook model is within 20% (and the vast majority within 10%) of the stratigraphic information, in terms of LTA thickness. The contrasting point is that the current numerical model does not match well with the stratigraphic information in this area:

- 17 of the 33 bores in Table 2.1 represent points where the stratigraphic information shows the LTA thickness is more than 20m different to the current numerical model.
- 10 of the 33 bores in Table 2.1 represent points where the stratigraphic information has a discrepancy of more than 50% compared to the current numerical model in terms of LTA thickness.
- Some of the most significant differences are where the current numerical model exhibits a much greater thickness than supported by the stratigraphic information. These are generally shown by the blue areas in Figure 2.1. In part this represents areas south of the Bambra Fault (e.g. the cluster of bores 114147 to 114149 and 307440). The Newlingrook project used mapping technology that could more rigorously incorporate the fault alignments into the aquifer geometry. The result is considered to be a more realistic and complex representation of the aquifer in the area around the Bambra Fault. This identifies an area for improvement in the numerical model.

  However there are also bores north of the fault such as 108914 and 108915 which have a greater LTA thickness than indicated by stratigraphic information – these bores are particularly significant in that they lie within an area of the model that is poorly calibrated in the current numerical model (these bores are reviewed later in Section 3 of this report as part of the drawdown analysis). It is very unlikely that the difference in LTA thickness alone would account for the poor calibration, but correcting the aquifer geometry in this area is likely to be a helpful step towards a better calibration.
- In contrast, there are some locations where the current numerical model layers have a lower LTA thickness than indicated by the stratigraphic information. (These areas are generally shown by the red and yellow areas in Figure 2.1). Bores 64237, 64227 and 64244 are examples of these sites – again they are important because they fall within the area between the borefield and Gellibrand catchment that is currently not well conceptualised or well calibrated in the current numerical model. For 64237 and 64244 the absolute difference in metres between the stratigraphic information is not large but the relative difference is significant; at 64237 the numerical model has a LTA thickness of 6m compared to the stratigraphic information of 19m, and for 64244 the difference is 17m in the model compared to 34m from the stratigraphic interpretation. It is unlikely that these differences in LTA thickness are the main reason for the poor calibration in this area, but improving the aquifer geometry in the model so that it is a closer fit to actual data is likely to contribute to a better calibration.

In summary, it is clear that the current numerical model does not match well with stratigraphic interpretation in terms of aquifer thickness. It is possible that during construction of the current numerical model layers, lithological data was used to modify the aquifer thickness (i.e. low permeability layers within the LTA were excluded from the thickness), however this does not explain the significant number of sites where the numerical model has a greater thickness than supported by the stratigraphic data. The review suggests that the current numerical model layers need to be revised in this area. Further, the review indicates that the Newlingrook model is a much better fit to the stratigraphic data and would be a logical starting place in reconstructing the model layers. A further important explanatory factor is that the stratigraphy of the area has been reinterpreted by the Geological Survey a number of times. The Barwon Downs model is likely using an earlier version of the stratigraphic interpretation that the Newlingrook model.

Bedrock elevation

In terms of bedrock (basement) elevation, the Newlingrook Model also most closely represents the available stratigraphic information in the south western area. In Table 2.1 there is only one bore in which the Newlingrook model bedrock elevation differs by more than 20m from the stratigraphic data. In contrast the bedrock elevation of the current numerical model does not match well with the stratigraphic information in this area; 16 bores (approximately 50%) show more than a 20m difference in elevation and 11 (33%) show more than a 40m difference.

As the Newlingrook model matches well with the stratigraphic data, Figure 2.2 provides a good indication as to how the current numerical model differs from the available stratigraphy. The figure shows that within the graben, in the south-west corner of the model, the elevation of the bedrock in the current numerical model is too high – the Newlingrook model has the bedrock elevation generally 10 to 100m lower through this area than the current numerical model.

As per the aquifer thickness, reviewing and correcting the bedrock elevation through this area is likely to contribute to a better calibration of the numerical model. Further, it is noted that in parts of the current numerical model through this area it is not just the shape and magnitude of the drawdown that is matched poorly but the groundwater heads in the aquifer are also poorly matched (nested bore site 64227 and64228 are a case in point). Improving the accuracy of the bedrock elevation could be an important change in improving the match to groundwater heads in this area.

South of the Bambra Fault, the elevation of the bedrock in the current numerical model is too low - the Newlingrook model has the bedrock elevation generally 10 to 100m higher on the up-thrown side of the fault compared to the numerical model. As described above, the methods employed in the Newlingrook project are considered more likely to provide a realistic representation of the bedrock elevation and aquifer in the area around the Bambra Fault.

Aquifer (LTA) elevation

In terms of LTA elevation, the difference between the Newlingrook Model and the Barwon Downs model are not as significant as differences between the LTA thickness and bedrock elevation. Again, the Newlingrook Model is a better representation of the available stratigraphic information in the south western area, however the differences are smaller in magnitude.

In Table 2.1 there are seven bores in the Newlingrook model where the LTA elevation differ by more than 20m from the stratigraphic data, compared to the 17 bores for the current numerical model. Figure 2.3 shows that in the south west area, the numerical model has an LTA upper surface that is higher in elevation than the Newlingrook model and higher than supported by the stratigraphic data. In the area around the surface water catchment divide (between the Barwon and Gellibrand catchments) and in the upper tributaries of Porcupine Creek, Figure 2.3 indicates that this difference is generally in the range of 10 – 50 metres, and in places in the range of 50-100m. Addressing these discrepancies in the current numerical model in terms of the LTA elevation may improve model calibration and groundwater head matching through this south west area.

Barwon Downs monocline

It is apparent that the monocline (a step-like fold in strata consisting of a zone of steeper dip) that has been included in the Newlingrook model is a significant difference between the two models (this is represented by the dashed black and white lines running NE-SW from Gerangamete Flats towards Kawarren). Given that in general the Newlingrook model has been shown to be a better match to the stratigraphic data than the current numerical model, inclusion of this feature in the structure of a new model would seem warranted. (At the same time, consideration needs to be given to the ability of the numerical model to handle such steeply dipping contours, e.g. effect on model stability). However, the extent to which the interpretation of Bore 64235 has been used in the Newlingrook model as a justification for the geometry (particularly the steepness) of the monocline should be reviewed; as later in this report, it is noted that the interpretation of the bedrock in the base of Bore 64235 is considered to be erroneous.

2.1.2 Northern area

Table 2.2 shows differences between the Barwon Downs Model, the Newlingrook Model and available stratigraphic information for the top of basement, top of the Lower Tertiary Aquifer and thickness of the Lower Tertiary Aquifer along the northern model boundary. The following observations are made regarding this information:

- The three northern most bores in this data set are 109134, 102868 and 102865 (refer Figure 2.1 for bore locations). The northerly location means they are the most informative bores regarding the accuracy and suitability of the model near the Birregurra - Colac fault. There are no significant discrepancies between either the Barwon Downs model data and the Newlingrook model data or between the Barwon Downs model and the stratigraphic information at these three bores, suggesting that there is no real improvement to be made to the model layers in this area based on the available bore data.
- Of the remaining bores in the table, only two indicate any significant discrepancies, Bore 47775 and Bore 102869. The Newlingrook model has the top of the LTA 80m higher at Bore 47775 (located east of Whoorel), which also results in an aquifer that is 80m thicker at this location. However this top elevation for the LTA does not appear to be supported by the stratigraphic data. A review of the rationale for this higher elevation in the Newlingrook model should be undertaken. At Bore 102869 the numerical model has the bedrock 40m lower and the top of the LTA 20m higher than both the Newlingrook model and as suggested by the stratigraphic data, resulting in an LTA discrepancy of 60m between the two models. This is therefore also a site for future review and potential revision in the model layers. (Noting that these bores are well south of the faults along the northern boundary, and addressing these issues will not address / improve conceptualisation of the fault).
- There are four additional bores of importance not shown in Figure 2.1:
  - Bore 56055 – This bore (south of Colac) is not in the numerical model domain and hence is not included in the analysis of difference with the Newlingrook model (or in Figure 2.1). The various stratigraphic interpretations do not record any LTA in this bore, however the lithological log indicates there is 4m of sand between 330-334 metres (which is where the bore is screened). The stratigraphic interpretations treat this as a sand within the Narrawaturk Marl, however the underlying clayey material could be weathered bedrock, in which case this sand does in fact represent the LTA. It is recommended that any future numerical model be extended this far north, and hence a decision will be required as to whether to interpret the sand in this bore as LTA. A regional interpretation of the extent of the LTA would indicate that LTA broadly present in this area and hence interpreting this bore as LTA is probably reasonable. Gamma logging of the bore may assist in this decision.
  - Bore 50056 - This bore is not plotted in Figure 2.1 as the layers show less than a 20% difference between the numerical model and the Newlingrook model at this location. Stratigraphic interpretation indicates that there is 39.8 m of LTA present in this bore.
  - Bore 109114 - This bore is not plotted in Figure 2.1 as the layers show less than a 20% difference between the numerical model and the Newlingrook model at this location. Stratigraphic interpretation indicates that there is 125 m of LTA at this location.
  - Bore 69497 – This bore is not plotted in Figure 2.1, as it is north of the current numerical model domain. Stratigraphic interpretation indicates that there is 11.7 m of LTA present in this bore.

  The numerical model extent should be expanded to include all of the four bores listed above.
- Aside from differences at locations where stratigraphic information is available, Figure 2.1 to Figure 2.3 indicate that there are differences between the two models which appear to be based on differences in interpretation of available data (and changes in interpretation over time). For example, south of the Birregurra - Colac fault, immediately west of Birregurra, the Newlingrook bedrock elevation is 10-50m lower than in the Barwon Downs model. Conversely, at the same location but on the northern side of the fault the bedrock elevation is 50 – 100m higher than in the Barwon Downs model and moving further west towards Colac, the difference is more pronounced, with the bedrock 100-200m higher. It is recommended that available information and methodology for the Newlingrook project are interrogated to determine the rationale and suitability of this different interpretation.

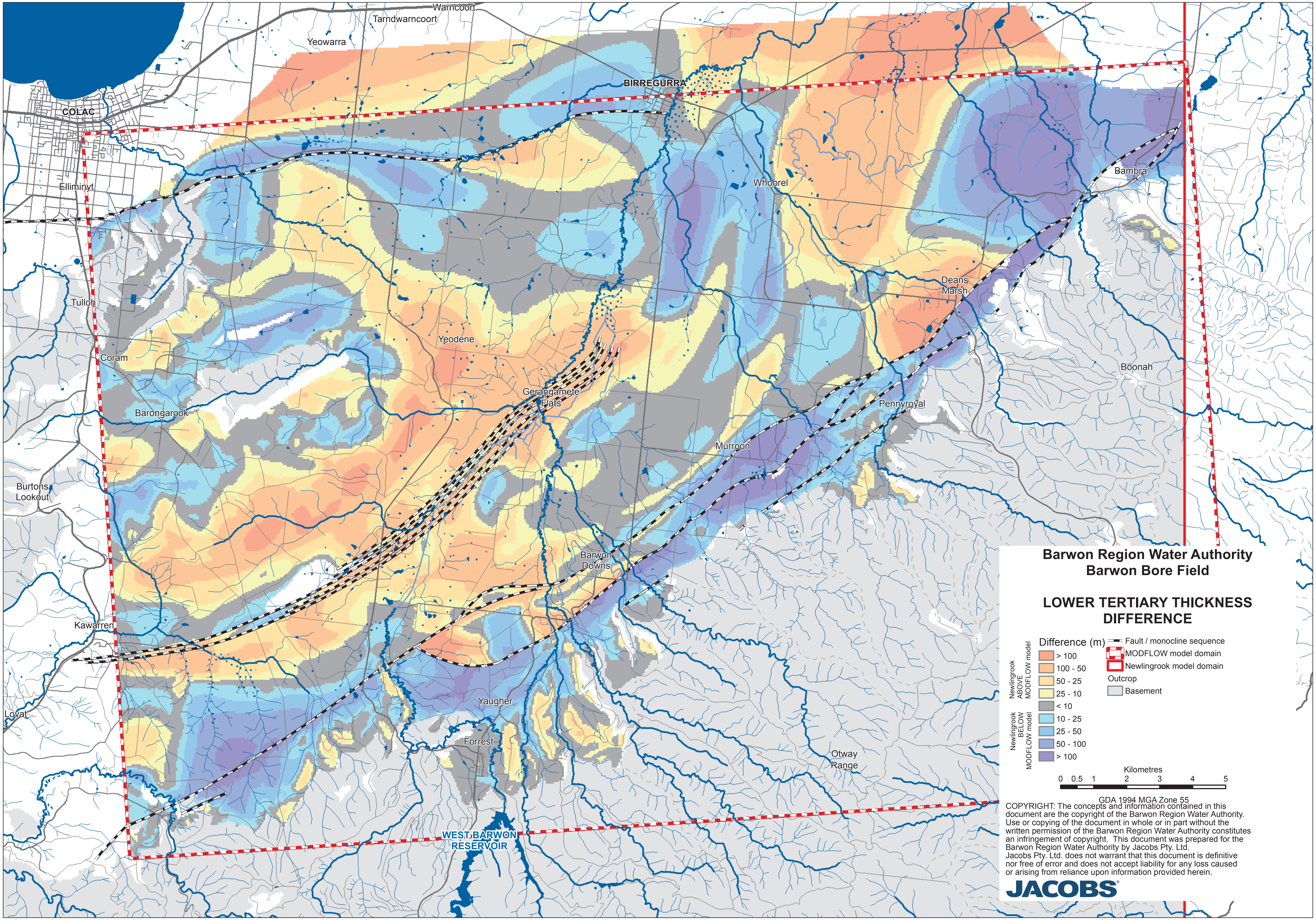
2.1.3 North east area

Although not within the original scope of this review, the north-east corner of the model is also worthy of comment. North of Deans Marsh and west of Bambra, Figure 2.3. indicates that the Newlingrook model places the top of the LTA between 10m and 100m deeper than in the current numerical model. The three key bores of relevance are bores 47774, 107720 and 107716. At these bores the top of the LTA in the Newlingrook model is 80m, 68m and 43m lower than in the current numerical model. The top of the bedrock is approximately the same in the two models, meaning that the difference between the models is an increased aquifer thickness (and thinner aquitard sequence) in the Barwon Downs model. At two of these bores sites, the stratigraphic information supports the Newlingrook model (at the third site, the stratigraphic information is significantly different to both interpretations, possibly suggesting an anomalous / inaccurate interpretation that appears to have been ignored during formation of both surfaces). In summary two of the three bores in the area support the interpretation of a lower top of LTA (i.e. the Newlingrook model).

This is an important area in terms of model predictions for drawdown in the aquitard. The current numerical model predicts that (in the long term, and dependent on actual borefield operation) there may be a significant amount of drawdown in this area, possibly up to 3-4m. This model prediction is largely driven by the thin aquitard in this area of the model. On this basis, this area has been identified as an area of significant PASS risk and possible PASS sites have been examined in the area. Three sites in this area have been identified at a desktop level as potential PASS risks, two have been field tested for PASS and on the basis of the field results one site will have a groundwater monitoring bore installed (to monitor watertable fluctuations, as part of a strategy to manage potential PASS risks in this area).

The significance of the Newlingrook model interpretation in this area is that if the LTA is deeper in this part of the model, as supported by the stratigraphic (and lithological logs) and the aquitard correspondingly much thicker, then the risk of watertable drawdown (and associated risks such as activation of PASS) is likely to be significantly lower than currently predicted by the numerical model. Hence this report recommends that this is an important area for review, and on the basis of this preliminary assessment, modification of the model layers.

Figure 2.1 : LTA thickness in the current Barwon Downs numerical model compared to the Newlingrook model



Refer to Jacobs document; I:\VWES\Projects\VW07575\Technical\Spatial\Working\ArcGIS\Conceptual_update_A3\lta_iso_diff_m_A3.mxd

Figure 2.2 : Bedrock elevation in the current Barwon Downs numerical model compared to the Newlingrook model

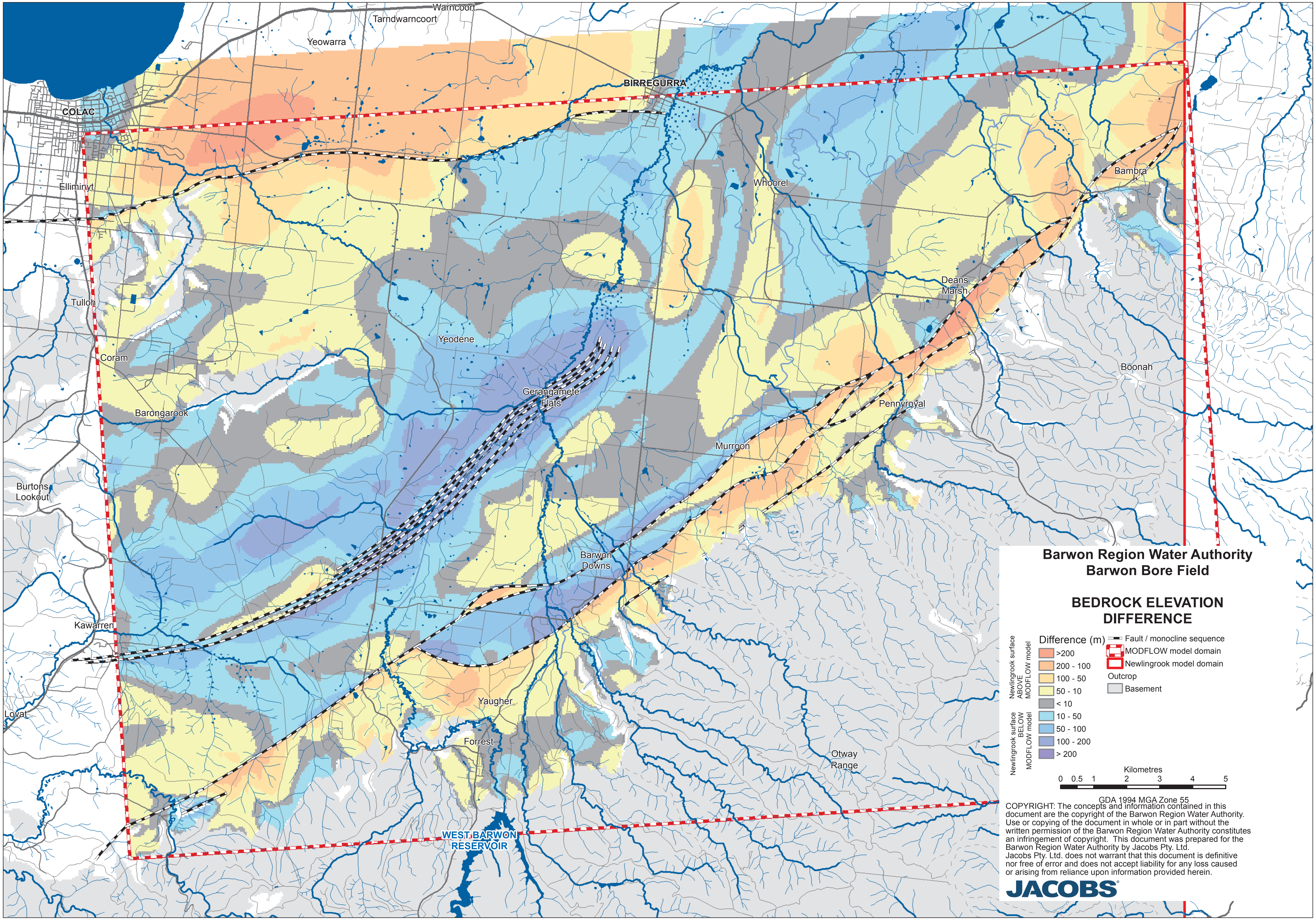


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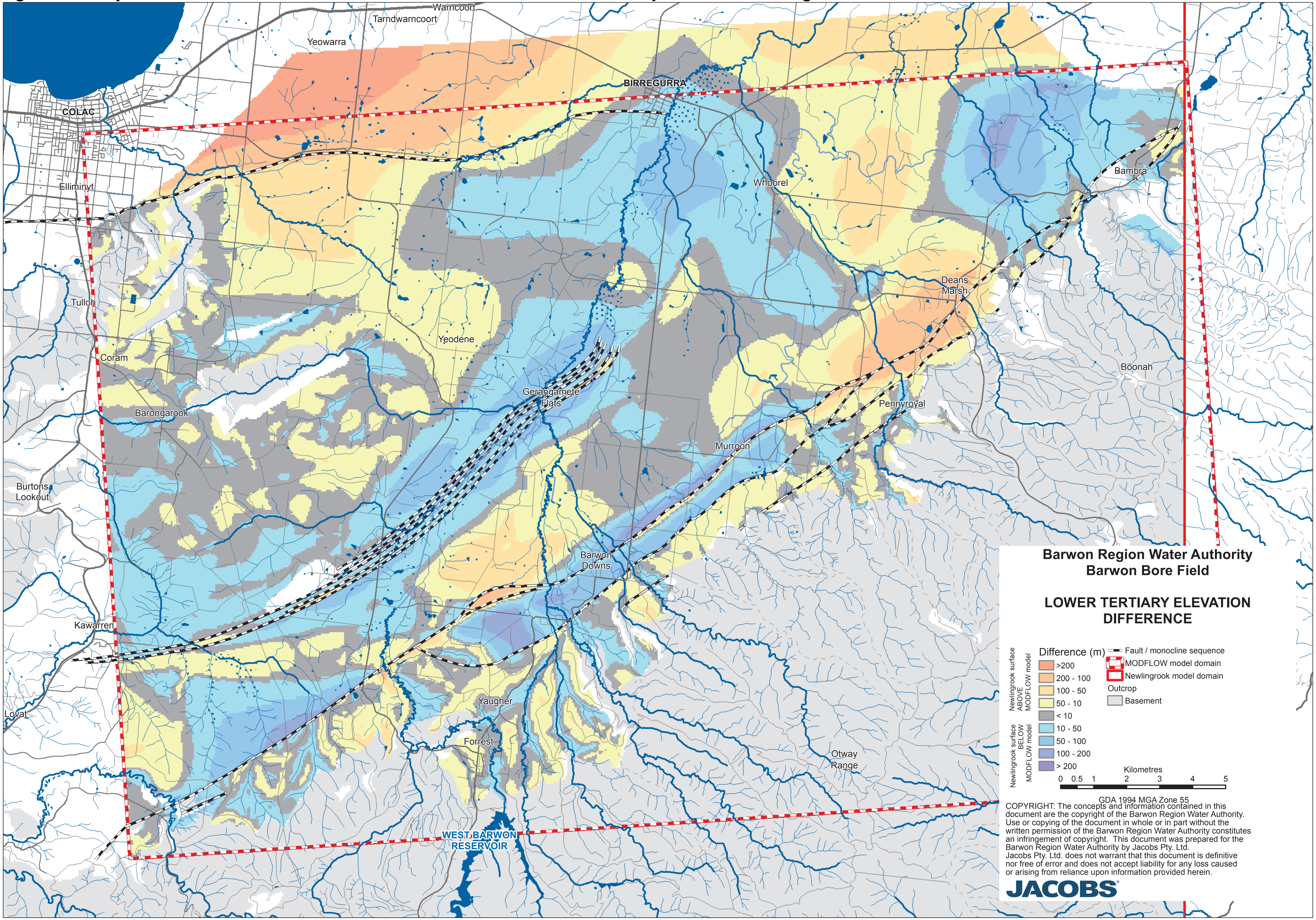
Figure 2.3 : Top of LTA elevation in the current Barwon Downs numerical model compared to the Newlingrook model



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Refer to Jacobs document; I:\VWES\Projects\VW07575\Technical\Spatial\Working\ArcGIS\Conceptual_update_A3\lta_diff_A3.mxd

Table 2.1 : The differences between the Barwon Downs Model, the Newlingrook Model and available stratigraphic information for the top of basement, top of the Lower Tertiary Aquifer and thickness of the Lower Tertiary Aquifer at the south western model boundary

Bore ID	LTA thickness difference %	Top of Basement (m AHD)			Top of Lower Tertiary Aquifer (m AHD)			Thickness of Lower Tertiary Aquifer (m) (1)			Bore stratigraphic information source (2)
		Barwon Downs Model	Newlingrook Model	Stratigraphic information	Barwon Downs Model	Newlingrook Model	Stratigraphic information	Barwon Downs Model	Newlingrook Model	Stratigraphic information	
114164	>500	186	**58**	58	201	**179**	130	15	**121**	72	b
114164	>500	185	**50**	64	199	**178**	136	14	**128**	72	a
64245	100-500	-359	**-333**	-333	-241	**-191**	-191	118	**143**	142	c
64237	100-500	-248	**-265**	-265	-242	**-246**	-246	6	**19**	19	d
G21 (64237)	100-500	-248	**-265**	-265	-242	**-246**	-246	6	**19**	19	c
64244	100-500	-19	**-41**	-38	**-2**	0	-4	17	**41**	34	a
BK56 (47988)	50-100	205	**204**	204	235	**251**	251	30	**47**	47	c
47988	50-100	205	**204**	204	235	**251**	251	30	**47**	47	f
114149	50-100	146	**232**	234	245	**249**	249	99	**17**	15	b
114148	50-100	210	**252**	252	248	**261**	261	38	**9**	9	b
114151	50-100	19	**14**	-33	154	**90**	47	134	**76**	80	e
64239	50-100	160	**151**	153	213	**225**	225	52	**74**	72	f
G23 (64239)	50-100	**154**	139	152	205	**224**	224	50	**85**	72	c
301540	50-100	171	**140**	138	**218**	230	216	46	**89**	78	c
114168	50-100	50	**-30**	-31	134	**105**	104	84	**135**	135	b
114168	50-100	52	**-27**	-31	136	**107**	104	84	**134**	135	a
334080	50-100	120	**138**	138	154	**181**	181	33	**43**	43	c
64241	50-100	-33	**-77**	-91	**121**	161	53	**153**	238	144	a
108914	20-50	-48	**-30**	-30	24	**21**	20	72	**51**	50	c

Bore ID	LTA thickness difference %	Top of Basement (m AHD)			Top of Lower Tertiary Aquifer (m AHD)			Thickness of Lower Tertiary Aquifer (m) [1]			Bore stratigraphic information source [2]
		Barwon Downs Model	Newlingrook Model	Stratigraphic information	Barwon Downs Model	Newlingrook Model	Stratigraphic information	Barwon Downs Model	Newlingrook Model	Stratigraphic information	
47996	20-50	166	**165**	164	251	**223**	223	85	**58**	59	f
BK64 (47996)	20-50	**165**	**165**	159	251	**223**	223	85	**58**	64	c
301543	20-50	188	**200**	202	254	**252**	252	66	**51**	50	c
48001	20-50	212	**214**	214	245	**250**	250	32	**35**	36	g
48003	20-50	-92	**-133**	-135	-23	**-43**	-46	69	**90**	89	g
64227	20-50	-256	**-292**	-292	**-194**	-190	-195	63	**102**	97	c
64241	20-50	-32	**-80**	-90	**121**	144	54	**153**	224	144	d
G25 (64241)	20-50	-32	**-80**	-89	**121**	143	55	**153**	224	144	c
307439	20-50	15	**19**	34	**155**	165	122	**141**	145	88	c
307440	20-50	10	**54**	53	**147**	156	121	138	**101**	68	c
108915	20-50	-38	**-26**	-25	54	**42**	43	92	**68**	68	c
114147	20-50	85	**98**	96	201	**197**	167	115	**98**	71	e
334081	20-50	160	**148**	147	**188**	191	180	**28**	43	33	c
BAMBRA	20-50	114	**149**	154	178	**201**	200	63	**52**	46	h
334083	20-50	120	**135**	131	**175**	176	175	55	**42**	44	c
114150	20-50	117	**158**	158	187	**213**	213	70	**55**	55	b
47996	20-50	166	**165**	164	251	**223**	228	85	**58**	63	a
108914	20-50	-46	**-28**	-27	**24**	23	24	70	**51**	51	a
48003	20-50	-93	**-134**	-135	-25	**-44**	-46	69	**90**	89	a
108915	20-50	-35	**-26**	-27	57	**42**	41	91	**68**	68	a

Notes:

1. Shaded rows indicate multiple (different) stratigraphic information at the same location
2. Bolded cells indicate the closest model to the stratigraphic information available

3. Stratigraphic data sources:

a) Victoria Stratigraphic Database

b) Stratigraphic analysis conducted for the Newlingrook model development – GMS-borelogs-HT1994june

c) Stratigraphic analysis conducted for the Newlingrook model development – Barwon Downs Model

d) Stratigraphic analysis conducted for the Newlingrook model development – GEDIS-Department of Manufacturing & Industry Development, Victoria

e) Stratigraphic analysis conducted for the Newlingrook model development – GEDIS-HT1994F

f) Stratigraphic analysis conducted for the Newlingrook model development – GEDIS-Department of Manufacturing & Industry Development, Victoria-HT1994june

g) Stratigraphic analysis conducted for the Newlingrook model development – Barwon Downs Model-HT1994june

h) Stratigraphic analysis conducted for the Newlingrook model development – SKM Drilling

Table 2.2 : The differences between the Barwon Downs Model, the Newlingrook Model and available stratigraphic information for the top of basement, top of the Lower Tertiary Aquifer and thickness of the Lower Tertiary Aquifer at the northern model boundary

Bore ID	LTA thickness difference (Newlingrook – Barwon Downs model), m	Top of Basement (m AHD)			Top of Lower Tertiary Aquifer (m AHD)			Thickness of Lower Tertiary Aquifer (m) (1)			Bore stratigraphic information source (2)
		Barwon Downs Model	Newlingrook Model	Stratigraphic information	Barwon Downs Model	Newlingrook Model	Stratigraphic information	Barwon Downs Model	Newlingrook Model	Stratigraphic information	
47775	81	-207	**-206**	-197	**-86**	-3	-92	**121**	202	105	a
109134	-7	49	**55**	55	88	**87**	87	39	**32**	32	b
109133	25	34	**25**	24	**178**	194	184	143	**168**	160	b
102869	-61	-406	**-362**	-361	-246	**-263**	-263	160	**99**	98	b
82844	12	-86	**-78**	-78	-30	**-10**	-7	56	**68**	71	b
62578	-9	**146**	159	150	204	**208**	213	**58**	49	63	a
109134	-6	47	**57**	59	86	**91**	91	39	**33**	32	a
102868	-24	-409	**-408**	-401	**-184**	-206	-178	**226**	202	223	a
102865	1	**-306**	-296	-306	-146	**-134**	-139	161	**162**	166	a

Notes:

1. Bolded cells indicate the closest model to the stratigraphic information available
2. Stratigraphic data sources:

a) Victoria Stratigraphic Database

b) Stratigraphic analysis conducted for the Newlingrook model development – Barwon Downs Model

Table 2.3 : The differences between the Barwon Downs Model, the Newlingrook Model and available stratigraphic information for the top of basement, top of the Lower Tertiary Aquifer and thickness of the Lower Tertiary Aquifer in the north-east corner of the model

Bore ID	**Top of LTA difference (Newlingrook – Barwon Downs model), m**	**Top of Basement (m AHD)**			**Top of Lower Tertiary Aquifer (m AHD)**			**Thickness of Lower Tertiary Aquifer (m) (1)**			**Bore stratigraphic information source (2)**
		Barwon Downs Model	**Newlingrook Model**	**Stratigraphic information**	**Barwon Downs Model**	**Newlingrook Model**	**Stratigraphic information**	**Barwon Downs Model**	**Newlingrook Model**	**Stratigraphic information**	
BA57 (47774)	-80	-66	**-53**	-53	163	**83**	83	229	**136**	136	b
47774	-81	**-60**	-46	-56	169	**88**	80	229	**134**	136	a
47773	64	**-107**	-103	-107	**89**	153	33	**195**	257	140	a
107720	-68	**-113**	-102	-109	**65**	-3	46	**177**	100	155	a
107716	-43	2	**0**	-47	196	**153**	146	**193**	153	193	a

Notes:

1. Shaded rows indicate multiple (different) stratigraphic information at the same location
2. Bolded cells indicate the closest model to the stratigraphic information available
3. Stratigraphic data sources:

a) Victoria Stratigraphic Database

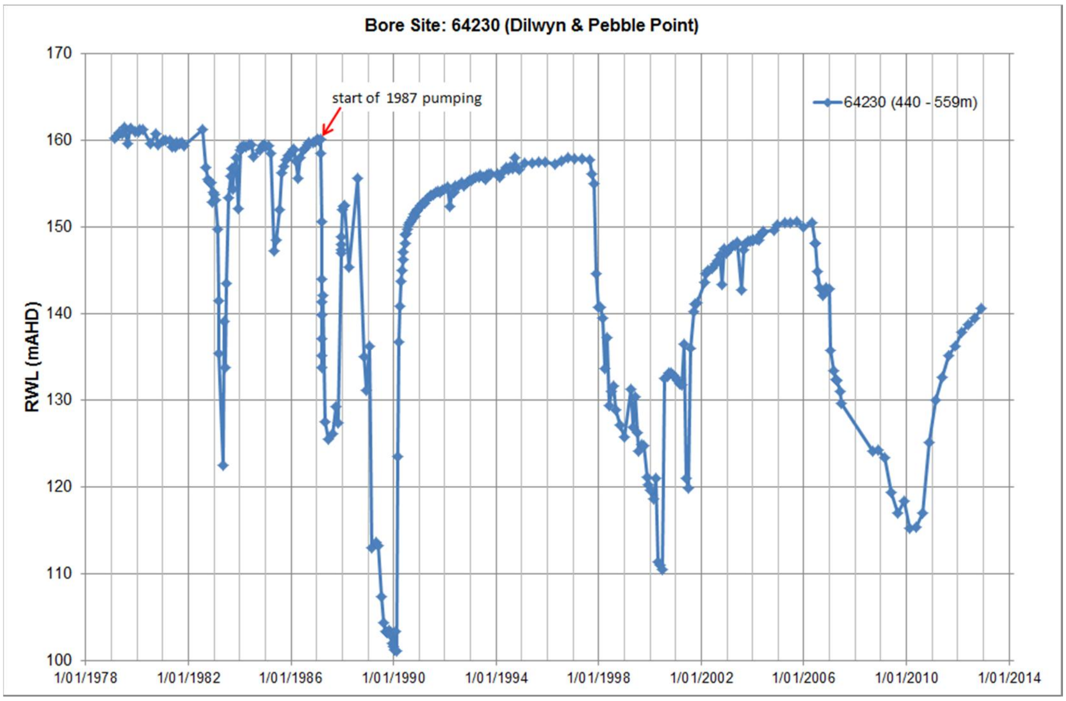
b) Stratigraphic analysis conducted for the Newlingrook model development – Barwon Downs Model

2.2 Review of potentiometric surface maps

Three potentiometric surface maps for the LTA aquifer were developed for this project – a pre-pumping groundwater surface (1987) and two post-pumping groundwater surfaces (2012 and 2014). The rationale for selecting the 2012 date was that an LTA drawdown map had been developed previously for Barwon Water for this date and hence it was a logical extension to produce a potentiometric surface map for the same date. The 2014 date was subsequently chosen to develop (as close as possible) a current potentiometric surface, and to observe any changes in water levels post 2012. It should be noted that 2012 is not a surface which represents the maximum drawdown, as the borefield was turned off in early 2010, meaning that water levels near the borefield had been in recovery for around two years. (However, at distance from the borefield in outcrop areas, groundwater levels in 2012 were lower than in 2010 due to the continued expansion of the drawdown cone at large distance from the borefield after the cessation of pumping).

Further information around dates and method for the maps is provided below:

- 1987 – the target date for water levels contributing to the map was 1 January 1987 and most of the data falls within 1 month of this date. The figure below is for 64230 which is located near one of the production bores. The hydrograph shows that even though there had been a small amount of test pumping prior to 1987, water levels were practically at full recovery by 1987. There were a small percentage of bores with water levels only available a number of months after this date (1/1/1987). As groundwater pumping commenced in March 1987, data after this date was only used where the bore was a large distance from the borefield, and hence with no impact from the borefield pumping (i.e. was still representative of a pre-pumping water level).



- 2012 - the target date for water levels used in the map was 1 August 2012. While this is a different season to the 1987 levels, the effect is relatively small compared to changes induced by the borefield. (The date was selected to coincide with previous drawdown mapping). Most of the data used in this map falls within 1-2 months of this date, however for 8 bores water levels were used up to 12 months from for this date. These bores were only used in order to infill key areas of the map that would otherwise be void of data, and where used, due consideration was given to possible changes due to the different date, e.g. adjustment was made to water levels based on bore trends, if necessary.
- 2014 - the target date for water levels contributing to the map was 1 August 2014. The date was selected to seasonally match with the 2012 map. Most of the data used in this map falls within 1-2 month of the

target date, however for 3 bores water levels were used up to 12 months from for this date (these bore were only used in order to infill key areas of the map that would otherwise be void of data, and with due consideration to possible changes due to the different date, e.g. adjustment to water levels made based on bore trend, if necessary).

It should be noted that the full complexity of groundwater levels around the Barongarook High area is not captured in the map. The outcropping LTA has multiple aquifers with different levels; these maps have tended to prefer deeper units and hence will overestimate drawdown in shallower units. (More accurate representation of the watertable on the Barongarook High and other outcrop areas is being developed for a separate project).

The contouring of levels was a combination of an automated and manual process. Initially contouring was conducted using an automated software package to produce the contours. The output from this was then manually adjusted in areas as required, e.g. to obtain reasonable fits in parts of the study area that could not be well represented, such as the Bambra Fault or other structural features.

Note that A1 maps have also been produced in association with this report which show the bore IDs and plot the groundwater levels which have been used in construction of these surfaces.

2.2.1 Pre-pumping groundwater levels

The 1987 LTA groundwater elevation map is shown in Figure 2.4. The following observations are made regarding these pre-pumping groundwater levels:

- The general pattern of groundwater flow, as per the current conceptualisation, is of radial groundwater flow away from the recharge area of Barongarook High, toward the north, east and south. What is new in this map is that an attempt has been made to define the different groundwater catchments for the LTA within the study area. The dashed pink line in the figure shows the interpreted groundwater divides and the associated three main catchments. (Note that if a finer resolution criteria was applied to the definition of the groundwater catchments, more than three catchments would be formed - but for the purposes of depicting regional groundwater flow, groundwater depressions less than 5m deep have been incorporated into the larger groundwater catchments. This same method for defining groundwater catchments has also been applied in the 2012 and 2014 maps). Note that the entire groundwater catchment is not shown for either of the three main catchments, which extend beyond the borders of the map. The three groundwater catchments include:
    - A northern catchment with the catchment divide starting several kilometres north of Boundary Creek and heading approximately towards Birregurra. Groundwater flow is dominantly towards the north.
    - A 'central' catchment which encompasses most of Boundary Creek and extends east, through Gerangamete Flats and towards Whoorel and Deans March. The southern boundary of this catchment runs approximately through the borefield. Groundwater flow is generally eastward in this catchment. Due to the regional nature of this mapping exercise, the sub-catchment which includes groundwater discharge to Boundary Creek is not shown within this map. As the groundwater catchment coarsely approximates the Barwon surface water catchment it is referred to in subsequent discussions as the Barwon groundwater catchment.
    - A southern catchment with a recharge area comprised of the south-west part of the Barongarook High LTA outcrop. The catchment divide runs approximately from Barongarook through to Barwon Downs. Groundwater flow direction is dominantly in a southerly direction in the upper part of the catchment, but south westerly in the lower part of the catchment. A significant portion of groundwater flow in this catchment will discharge to the Gellibrand River. As the groundwater catchment roughly approximates the Gellibrand surface water catchment it is referred to in subsequent discussions as the Gellibrand groundwater catchment.

A point of interest that has been raised by the community in various stakeholder engagement forums is the location the groundwater divide between the Barwon and Gellibrand groundwater catchments, and the impact on this divide due to groundwater pumping. Figure 2.4 shows that the location of the groundwater divide between these catchments is not coincident with the surface water divide. In the upper west part of the Gellibrand groundwater catchment, the catchment extents approximately 2-3km into the Barwon surface water catchment. In the upper eastern part of the groundwater catchment the Gellibrand groundwater catchment extends more than 5 km into the Barwon surface water catchment. For example the township of Barwon Downs is interpreted to lie within the Gellibrand groundwater catchment, and the borefield itself essentially straddles the groundwater divide. (The issue of changes to the groundwater divide due to pumping is discussed later in this section).

This conceptualisation is different to past conceptualisations which considered the Gellibrand and Barwon groundwater and surface water catchments to be more closely matched. It is worth noting however that the location of the divide is difficult to define precisely; because the potentiometric surface is very flat in the area of the borefield, a greater resolution of contours is required to pin this down with more accuracy, and also the location of the groundwater divide is subject to change with relatively small changes in groundwater levels (including changes induced by both natural and anthropogenic factors).

- The change in groundwater gradients across the map is also instructive. The groundwater gradient in the Barongarook High outcrop (unconfined) areas is generally relatively steep but in the northern and Barwon groundwater catchments this gives way to much flatter gradients as the aquifer transitions to confined conditions, indicative of relatively higher transmissivity. In contrast, in the 'Gellibrand' groundwater catchment the groundwater gradient in the transition to the confined aquifer is characterised by a continuation of the steep gradients in the outcrop area. In fact these steep gradients extend eastwards to where the Barwon River west branch flows off the bedrock onto the Barwon River flood plain (refer to the 120 to 150m contour lines in Figure 2.4). Compared to the flat gradients near the borefield, these tight groundwater gradients (approximately 4km south-west of the borefield), are indicative of some type of change in the aquifer through this area, such as lower transmissivity. This is important because it the same conclusion reached about this area from the drawdown analysis in Section 3, and will be referred to later in this report. The steep gradient in the upper Gellibrand groundwater catchment changes to a much flatter gradient through the Kawarren area. This is consistent with the higher transmissivity that is known through this is area, e.g. from groundwater investigations and associated hydraulic testing in the 1980s and more recently in the late 2000s, as part of the Newlingrook groundwater investigation.

- The final point to note regarding the pre-pumping groundwater levels is that there are several locations where the LTA aquifer is interpreted to be unsaturated. These are the dark grey areas in the map (the light grey areas are outcropping bedrock). There are two main areas where the map indicates unsaturated LTA is present:

  - The central area of the Barongarook High, adjoining and south of the bedrock outcrop area - the primary cause of the unsaturated area is the relatively shallow bedrock mapped in this area in the Newlingrook model (the geological layers underpinning the potentiometric surface maps are from the Newlingrook model). There was a new bore added in the middle of this 'unsaturated' (dark grey) area during the 2014 drilling program (TB5). It is apparent from TB5 that the bedrock is not as shallow as mapped in the Newlingrook model and hence this area of unsaturated aquifer for pre-pumping conditions is over-estimated. Whether the material encountered at around 26m in TB5 is weathered bedrock is a matter requiring further consideration – e.g. comparing the gamma log response to other areas of known weathered bedrock – but whether it is mapped at 26m below ground or deeper, the result will still be an aquifer that is saturated rather than unsaturated at TB5. (The water level in 2014 sits at about 21m below ground level at this point). Hence the extent of the unsaturated area of aquifer is overestimated and should be corrected by incorporating information from the 2014 bores into the aquifer geometry. (This issue also raises the question of how this area – where the watertable resides in the bedrock – should be modelled. Currently the bedrock is modelled as a no-flow boundary, but given the important location of the bedrock outcrop, i.e. in the central part of Boundary Creek, this conceptualisation should be revisited).

- o A small area in the south west of the Barongarook High – this is caused by a small zone of relatively shallow bedrock.

An additional area worthy of comment, although not an area of unsaturated LTA, but an area where the LTA is mapped as absent, is the elongated zone of around 2km length in the middle of the Barwon Downs Graben (south west of the borefield). This is considered to be an anomaly caused by misinterpretation of the log for Bore 64235 (this bore is in the middle of this zone). This lithology log (from the geologist) for this bore describes the interval 183 – 192m as “white limestone and grey marl”. The drillers log describes the same material as sandstone, which is where some of the confusion may have arisen. (The geologist log should take precedence, unless there is a good reason otherwise). There are two stratigraphic interpretations for this bore, one has Clifton Formation from 161.2 to 187.5m underlain by bedrock at 187.5m. The second has Clifton Formation from 161 to 192.5m. It is apparent that the Newlingrook mapping uses the former interpretation, which results in the area around the bore mapped as the LTA being absent. The latter interpretation is considered to be correct – if the Newlingrook model is used as a starting point for new model layers, it is recommended that this point be corrected to reflect this change.

2.2.2 Post-pumping groundwater levels

The discussion below includes consideration of how groundwater divides and catchments have changed under groundwater pumping. It is important to bear in mind however that groundwater catchments are not static (unlike surface water catchments) and vary naturally in response to seasonal and long term climate variations in recharge and discharge rates.

2012 Groundwater Levels

Figure 2.7 to Figure 2.9 presents a sections of the potentiometric surfaces for the three dates examined, which assists in understanding the following discussion. Key issues to note regarding the 2012 potentiometric surface include:

- The groundwater divide separating the Barwon and Gellibrand groundwater catchments has subsided, and the two catchments are merged into one large groundwater catchment, where (within the graben) groundwater flows in a south westerly direction. (The Barwon-Gellibrand groundwater divide is essentially unchanged through the unconfined area – it is through the confined part of the aquifer that the divide has subsided). There is a new catchment divide which has been established that sits approximately between Birregurra and Deans Marsh. The Barwon groundwater catchment (as defined above for the pre-pumping scenario) lies on the north eastern side of this divide. It is worth noting however that the gradients within this area of the changed groundwater catchments are very flat and hence it is difficult to define precisely the exact location of the divide.
- Groundwater gradients towards the Gellibrand River are essentially unchanged. (This can be seen more clearly in the potentiometric long section in Figure 2.8). This means that the change in groundwater discharge to the Gellibrand River will be very small. (It should also be noted that there is ongoing consideration of the extent to which groundwater level decline of bores in and south of Kawarren area is due to the Barwon Water borefield pumping, versus other processes, such as local pumping. This theory has some merit, because there is one bore (48003) screened in the LTA which lies between the Kawarren area and the borefield which shows no groundwater decline). (It is recommended that the extent of local groundwater pumping in the Kawarren area be determined – via consultation with SRW – to assess whether this could explain the drawdown observed in the Kawarren area).
- The boundary between the Barwon and northern groundwater catchment has moved slightly to the north, by approximately 1 to 2km, compared to the pre-pumping (1987) case.

- In the eastern part of the Barongarook High along Boundary Creek (downstream of the bedrock outcrop area) the contours indicate that LTA aquifer water levels have dropped by around 5 to 10 metres (20m in the very eastern edge of the outcrop area). The shape of the contours around Boundary Creek which were indicating gaining conditions are now indicating neutral to losing conditions. It is important to note however that the scale of this map is not suitable for highlighting the detail of groundwater levels around Boundary Creek. Further, due to aquifers within the LTA exhibiting different heads in this area, the shallow groundwater levels which are interacting with the creek or swamp may not be highlighted in this figure.
- The area within the Barongarook high where the LTA is unsaturated (and the watertable resides in the bedrock) has expanded slightly - grown towards the borefield by approximately 200 – 300m. (As noted earlier in this report, the extent of this unsaturated area is likely to be significantly overestimated due to the inaccurate bedrock surface used to define this zone).

2014 Groundwater Levels

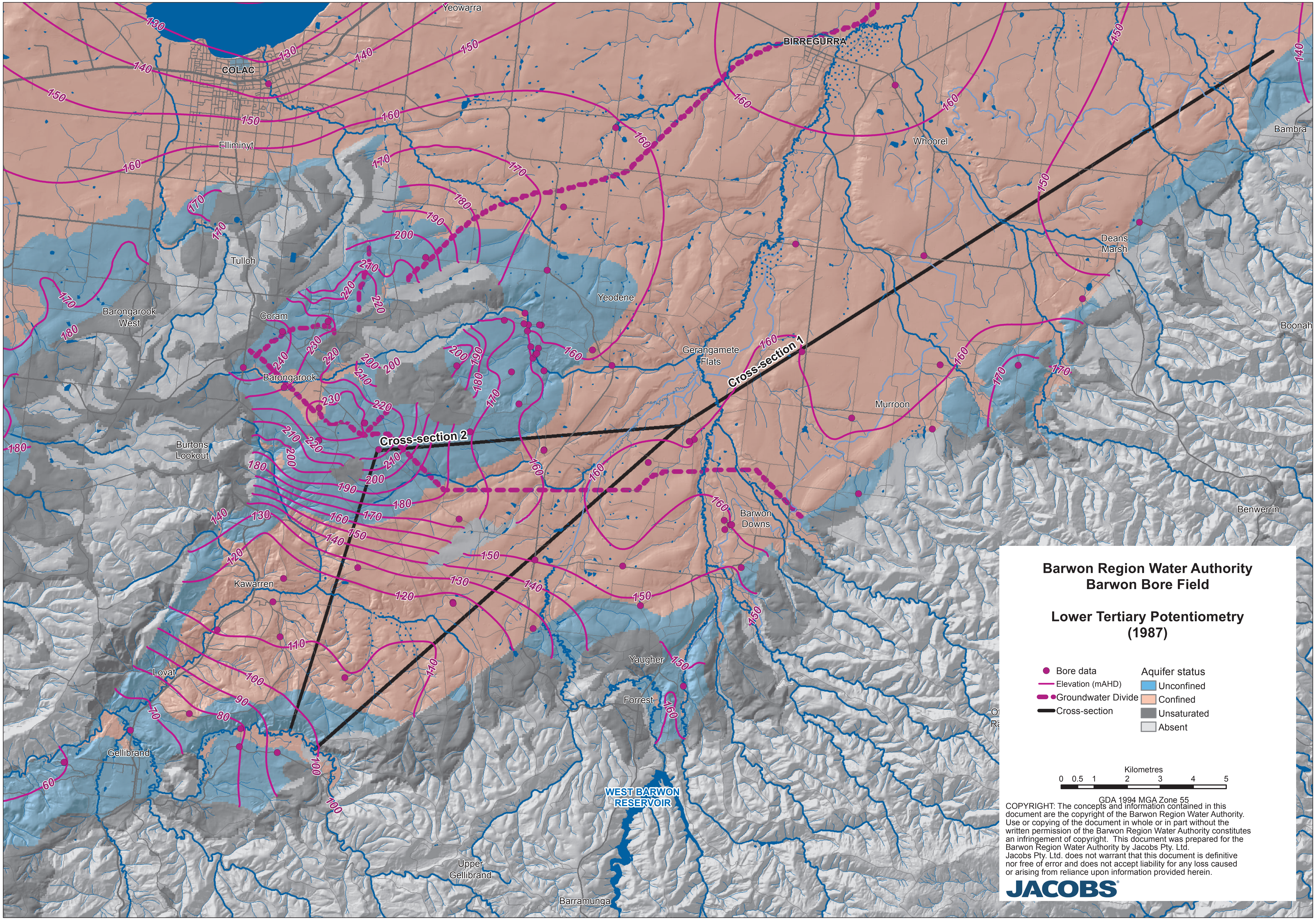
Recovery of groundwater between 2012 and 2014 results in the re-establishment of the groundwater divide between the Gellibrand and Barwon groundwater catchments, although it is between 2-4km to the south-west of the pre-pumping divide. This will migrate north east as groundwater levels recover. Another change between the 2012 and 2014 groundwater levels is the south-west migration of the Barwon catchment divide (by approximately 2-4km). This divide will migrate further south-west as groundwater levels recover.

The sum of these changes, is that compared to the 1987 groundwater levels, there are now actually four main groundwater catchments, with the ‘new’ catchment being the borefield catchment, where regional groundwater flow direction is towards the borefield. The catchment divide referred to above as the Gellibrand - Barwon catchment divide, is therefore more correctly called the Gellibrand – borefield catchment divide. As levels near the borefield further recover, the groundwater catchment divide between the Barwon catchment and the borefield will disappear and the three main catchments, as per the pre-pumping case, will be re-established.

A critical point to emphasise at the end of this discussion, is that while examining how groundwater divides and flow patterns have changed compared to pre-pumping levels is of interest and helps in some way in the conceptualisation of the groundwater system, it can also be misleading in that it is not an accurate guide to potential impacts of the borefield. For example, an issue of concern raised in the past by the community is what impact the borefield operation may have on the Gellibrand catchment and Gellibrand River flows. While this analysis indicates that there is likely to have been some impact, and a groundwater divide subsiding or migrating may sound significant, by its very nature groundwater pumping inherently alters the flow direction and flow paths of groundwater, and hence will change groundwater catchments. (As noted previously, groundwater catchments and divides are inherently dynamic and change under naturally varying patterns of recharge and discharge). Hence consideration of changes in groundwater divides and flow direction alone is not very helpful, because it does not inform regarding the impact of pumping which could range from negligible to significant.

When considering the Gellibrand River for example, what is more important is how groundwater pumping has changed flux (i.e. rate of discharge to the river). While the potentiometric data shows that the groundwater divide between the Barwon and Gellibrand subsiding between the 1987 and 2012 dates (and hence presumably also during and after periods of groundwater pumping) this does not necessarily mean a significant impact on the Gellibrand River has occurred. Indeed, evidence such as groundwater gradients near the river suggest that any impact is likely to have been very small. However, this would need to be confirmed via a numerical model. This raises an important point regarding the domain of the current numerical model, which only includes a small part of the upper Gellibrand River, and is hence not capable of determining these impacts. A recommendation from this review is that the current model domain should be expanded in a south west direction, to the approximate extend covered by the groundwater level maps (Figure 2.4 to Figure 2.6).

Figure 2.4 : 1987 Lower Tertiary Aquifer Potentiometry



Refer to Jacobs document; I:\VWES\Projects\VW07575\Technical\Spatial\Working\ArcGIS\Potentiometry\rwl_1987_A3.mxd

Figure 2.5: 2012 Lower Tertiary Aquifer Potentiometry

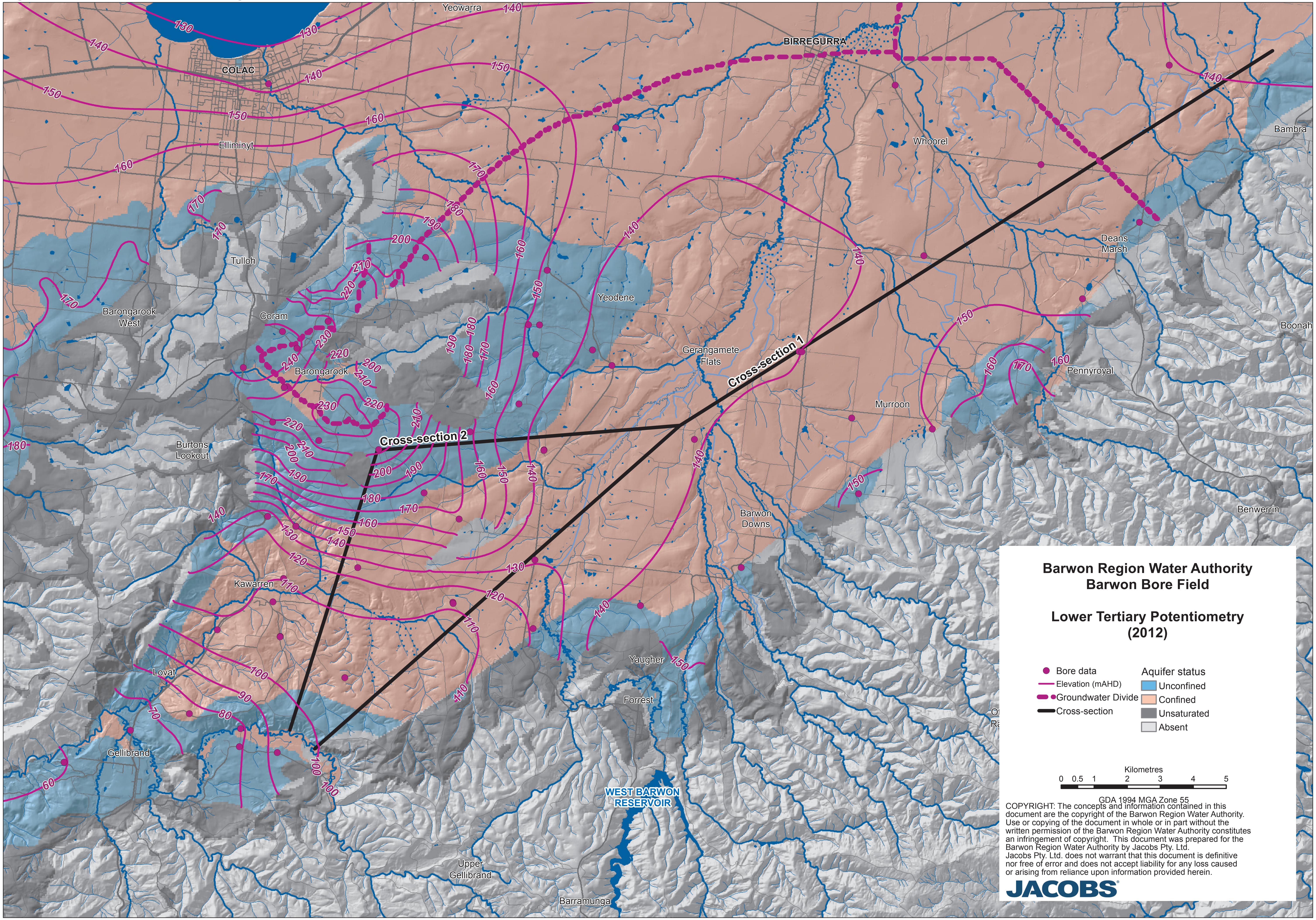


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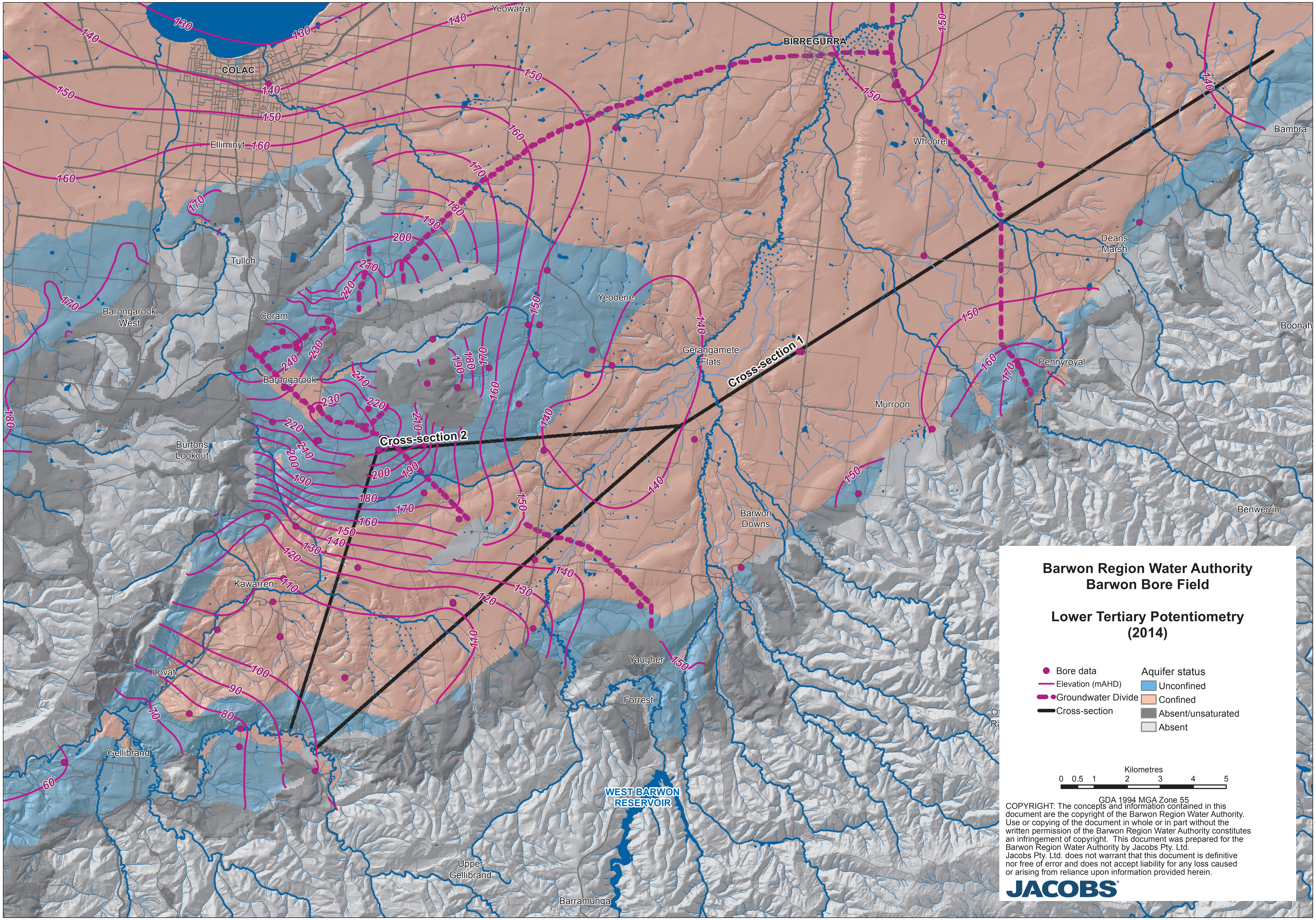
Figure 2.6: 2014 Lower Tertiary Aquifer Potentiometry



Refer to Jacobs document; I:\VWES\Projects\VW07575\Technical\Spatial\Working\ArcGIS\Potentiometry\rwl_2014_A3.mxd

Figure 2.7: Potentiometric Section Along the Barwon Downs Graben (Cross Section 1 in Figure 2.4 to Figure 2.6)

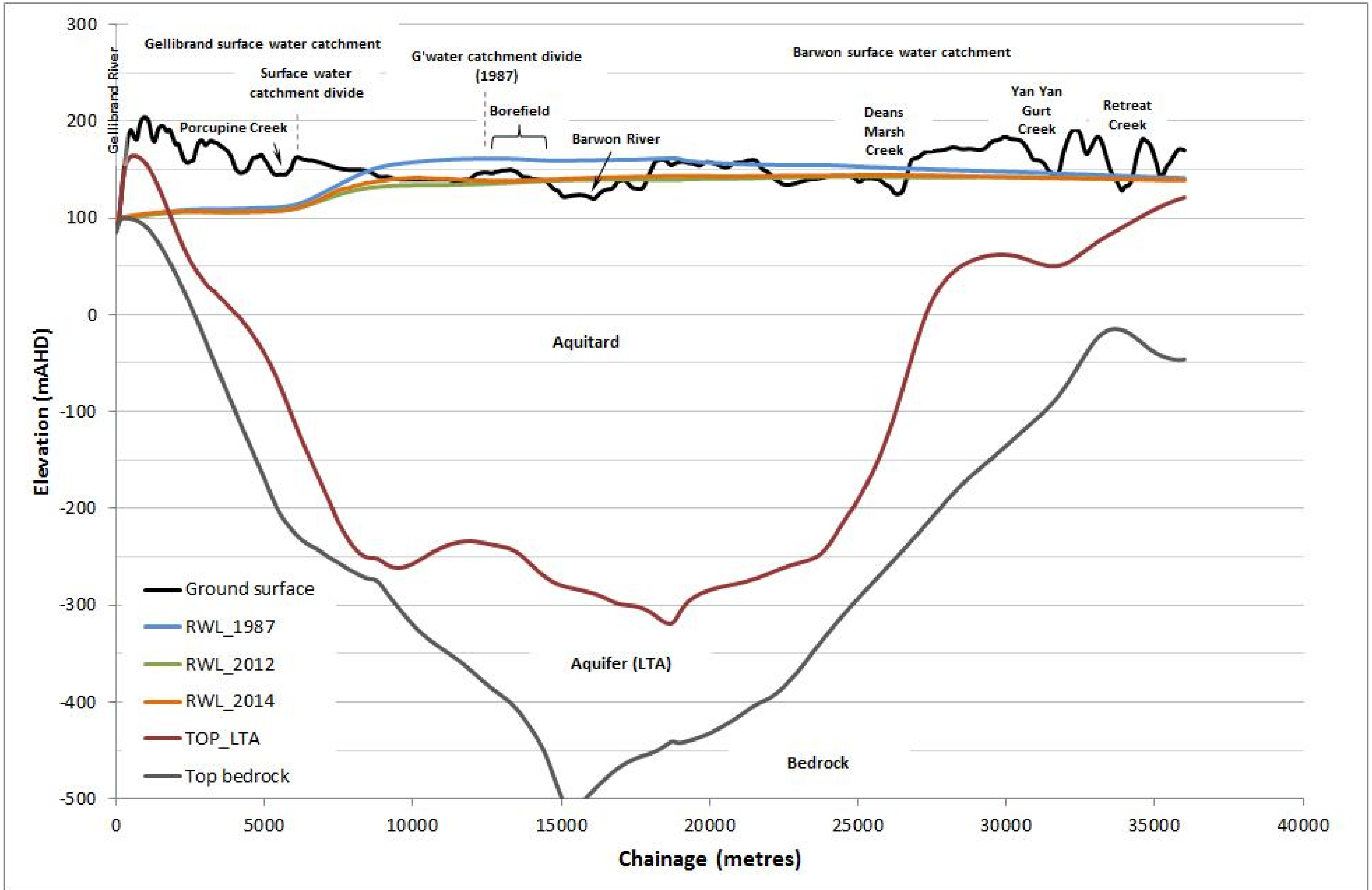


Figure 2.8: Potentiometric Section Along the Barwon Downs Graben (Cross Section 1 in Figure 2.4 to Figure 2.6). This is the same as Figure 2.7 but with an increased scale on the vertical axis

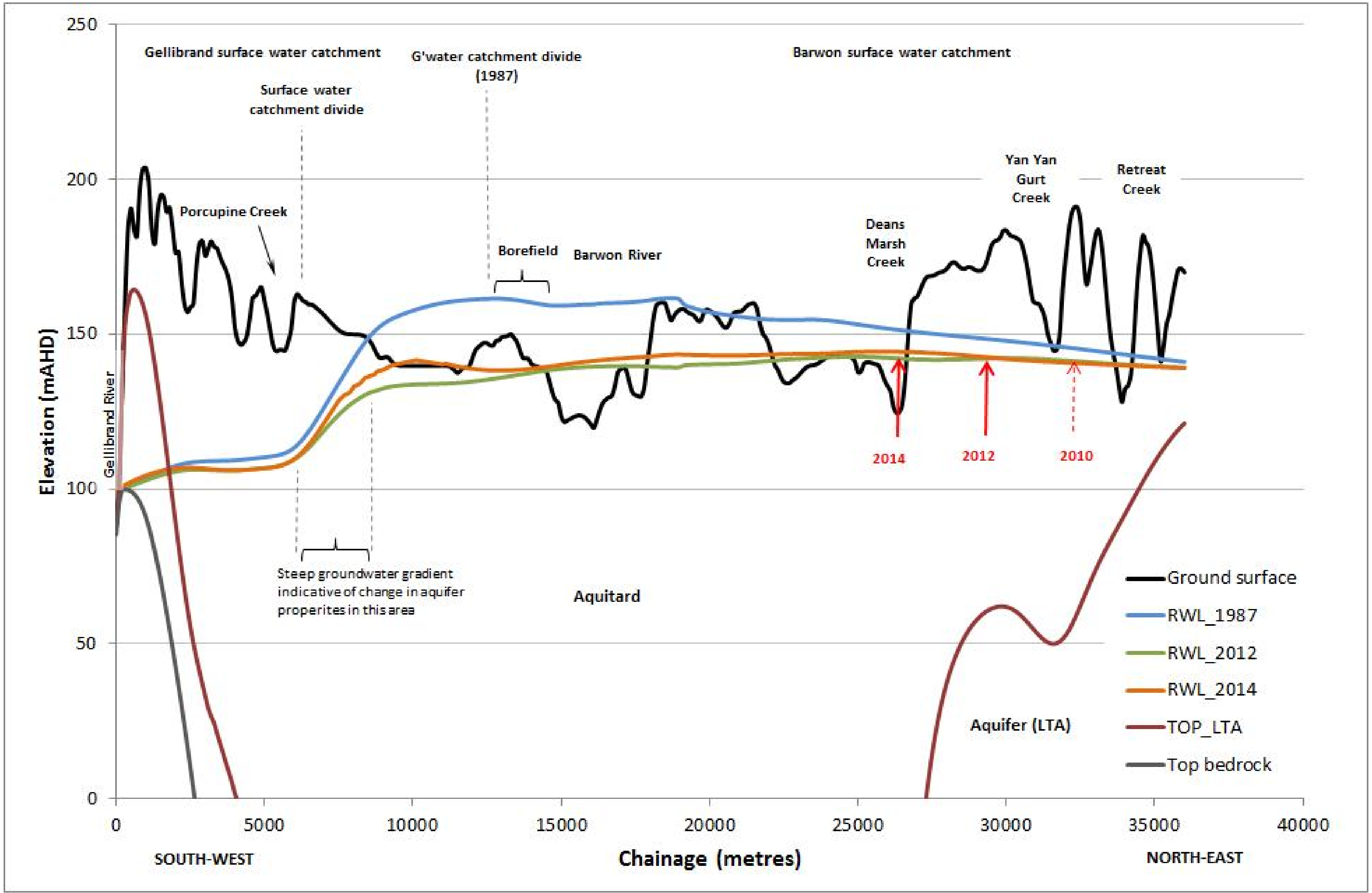
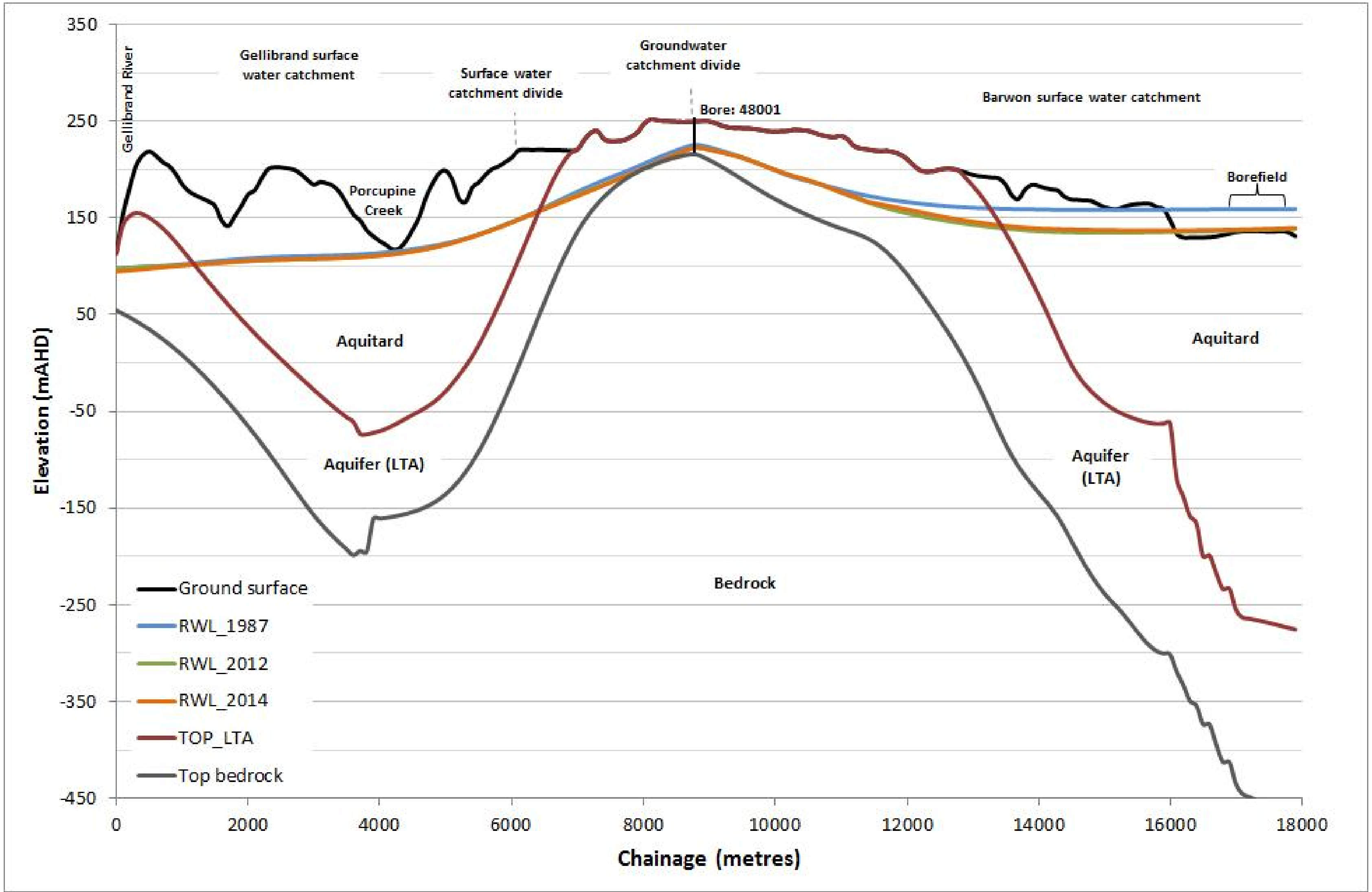


Figure 2.9: Potentiometric Section Across the Barwon Downs Graben (Cross Section 2 in Figure 2.4 to Figure 2.6)



3. Drawdown analysis

The purpose of this task was to use analytical pumping test methods to identify which aquifer models (e.g. leaky, bounded etc) best fit the drawdown data (i.e. change in groundwater levels over the period of the Barwon Downs borefield operation) within the two areas of interest. In the process, it is envisaged that the conceptual understanding of the area will be advanced, such as via identification of the location of boundaries or low transmissivity zones.

The analysis has been undertaken using the software package AQTESOLV. This part of the project was undertaken by mdGroundwater. The full report is presented in Appendix B. A summary of the results, key messages and recommendations is provided in this section.

The drawdown used in the analysis was calculated from the start of the first main period of borefield pumping, which commenced in March 1987. It is assumed that drawdown during short periods of pumping during the construction of the borefield prior to 1987 would have fully recovered before the March 1987 and, hence, not impact on this analysis. (Evidence supporting this position is presented in Section 2 of this report).

The analysis further assumes that the Dilwyn, Mepunga and Pebble Point formations form a single aquifer (i.e. there are no aquitards between these units). This is based on the rationale that all three units are intersected and pumped by the borefield and hence drawdown is expected to propagate in all of these units. Finally, the analysis has not been adjusted for any long term groundwater trends due to non-pumping effects, such as drought.

3.1 South West Area

3.1.1 Method

A total of ten observation bores monitoring the LTA in the area between the borefield and the south western margin of the model domain were selected for the analysis of this part of the model (refer Figure 3.1). These bores were selected due to their relatively long monitoring record (commencing prior to or at the same time as the borefield operation commenced), and their location between the borefield and the Gellibrand sub-catchment. The water levels from these observation bores have been converted to drawdown after commencement of pumping.

As a starting point in the analysis, drawdown in the bores since start of borefield operation was plotted, as shown in Figure 3.2. The figure shows that the drawdown in the ten observation bores are divided into two distinct groups, one with a rapid response to the three periods of pumping, and the other with a very subdued response to pumping.

In a homogeneous aquifer drawdown should propagate uniformly in all directions, and decrease in a uniform manner at increasing distance from the site of pumping. The Theis model is used to predict drawdown in a homogenous aquifer. Use of the Theis analysis as the first model applied in this review provides an indication of the extent (and location) of bores which don't fit with this homogeneous aquifer model. An example of this output is shown in Figure 3.5, with the dashed line indicating where the 'subdued response' bores are expected to plot in the Theis model. The figure shows that drawdown in the subdued bores is 15 to 30 times lower than expected if the aquifer had uniform hydraulic properties, i.e. a homogeneous aquifer with similar properties to those for the rapid response bores.

In addition to the poor fit for the six bores at greater distance from the borefield, the recovery phase of the rapid response bores fits more poorly to observed data after each period of pumping. This tends to indicate non-uniform aquifer conditions typical of a boundary or boundaries, or variable storage properties (i.e. presence of confined and unconfined conditions). The main report (in Appendix B) shows how an improved fit to the later recovery periods can be obtained by reducing the transmissivity and increasing the storage co-efficient which tends to indicate varying aquifer transmissivity and storage coefficient.

In summary, the results from the simplest analytical model (the Theis confined aquifer model) indicates that the aquifer is non-uniform (i.e. heterogeneous), and potentially of limited areal extent (i.e. bounded). Semi-confined (i.e. leaky) aquifer conditions and/or unconfined conditions (e.g. the Barongarook High) may also be present, as indicated by the high storage co-efficient for the subdued bores. The following section summarises the results when the potential for the aquifer to be semi-confined, bounded, or heterogeneous were assessed.

Figure 3.1 : Location of Lower Tertiary Aquifer observation bores used for analysis in the south west area, and LTA thickness (modified after SKM figure I:\VWES\Projects\VW04085\Technical\spatial\gw_model\spatial\arcmap\lta_iso.mxd)

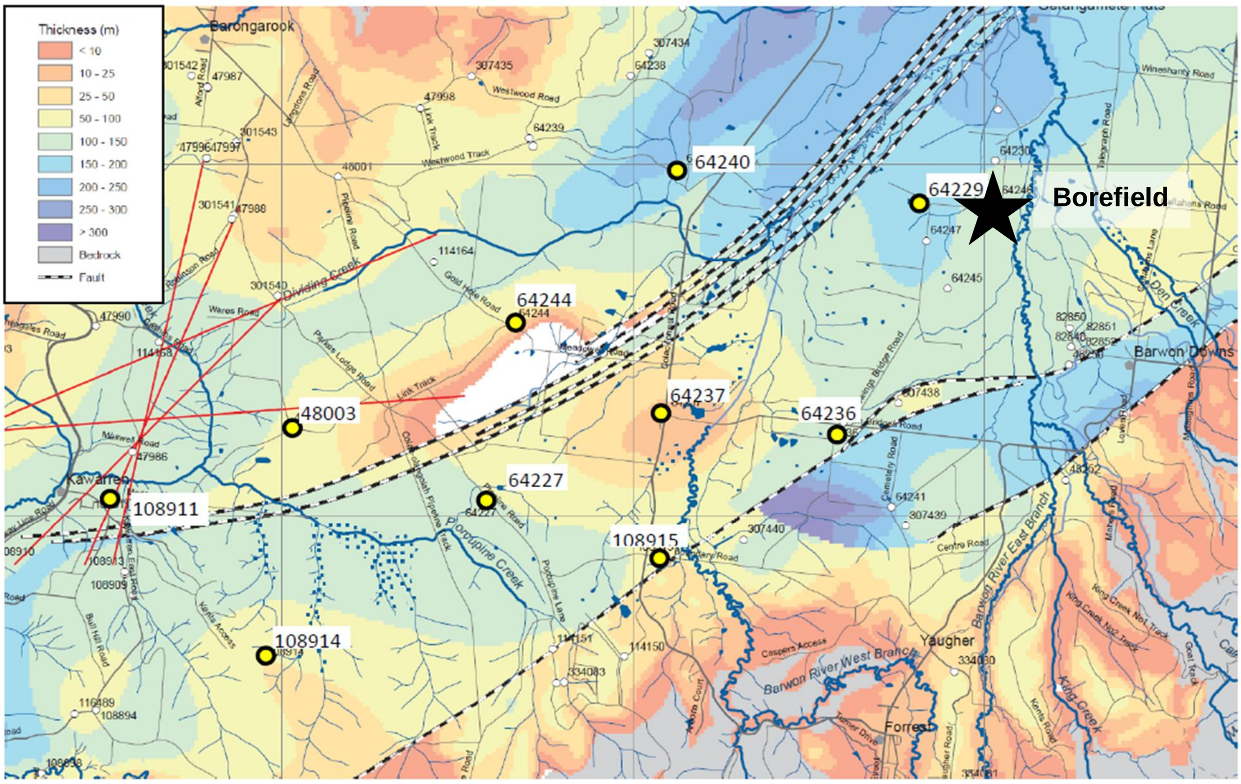


Figure 3.2 : Drawdown in the selected LTA bores for the south-west area since start of bore field operation in 1987

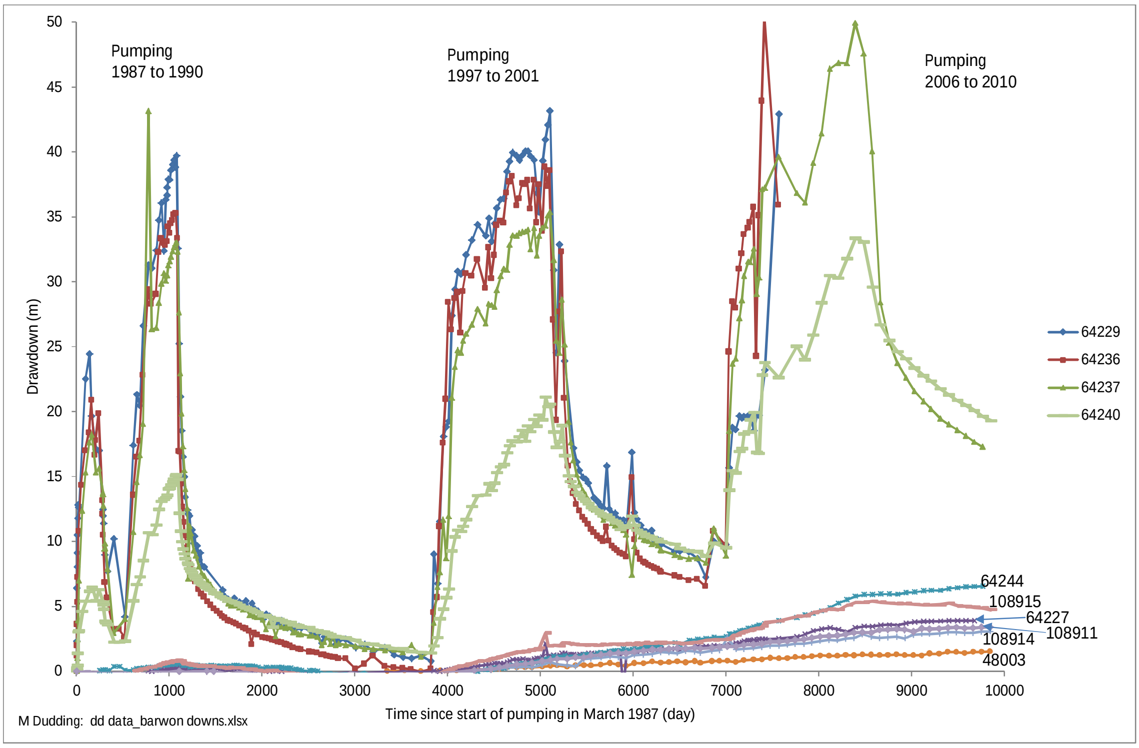
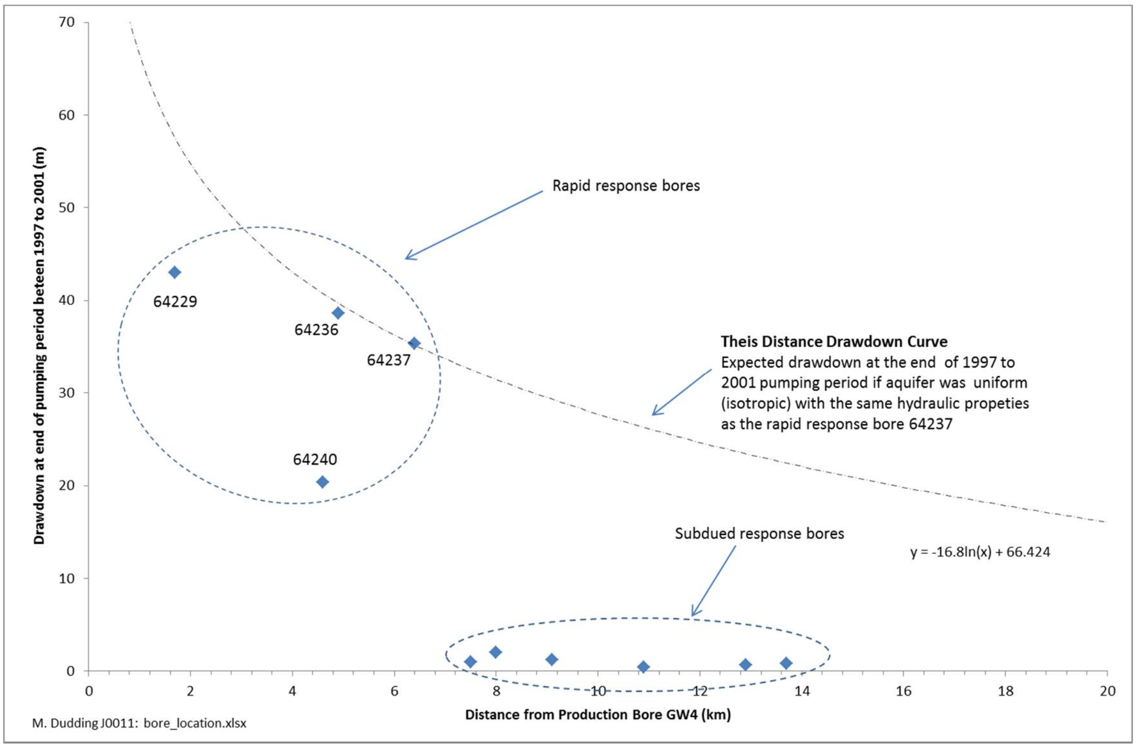


Figure 3.3 : Relationship between drawdown at end of 1997-2001 pumping period and distance from bore field (GW4)



3.1.2 Summary of results

A summary of the results of the drawdown analysis for semi-confined, bounded, and heterogeneous aquifer models is presented below:

- **Semi-confined aquifer analysis** – The Hantush (1960) analytical model (for leaky aquifer analysis) was applied, and provided an improved match to the rapid and subdued response bores compared to the confined Theis model. This is likely due to the lower transmissivity in response to the model allowing leakage of groundwater into the aquifer. The match to the subdued bores is however still relatively poor. Nevertheless, the improved match indicates that semi-confined conditions may be a contributing factor to the low drawdown in the subdued bores. (Results of this analysis are presented in Section 2.2.2. of the report in Appendix B).
- **Bounded aquifer analysis** – A bounded aquifer analysis was undertaken for a confined and semi-confined scenario. (Results of this analysis are presented in Section 2.3.1 and 2.3.2 of the report contained in Appendix B).
  - *Confined model*: the rapid response bores showed very little improvement in the match to the recovery data during the 2nd and 3rd non-pumping periods by incorporating a single boundary within the aquifer (representing the aquifer contact with the bedrock, located 5 km to the south of the bore field). Similarly little or no improvement to the match for the subdued bores was obtained. Including a second aquifer boundary (representing the Colac-Birregurra Fault and aquifer/bedrock contact near Colac) further degrades the match to both groups of bores. However, the two boundary model does display slower recovery rates after each period of pumping, indicating that the aquifer is non-uniform and most probably variability in transmissivity rather than only an abrupt termination of the aquifer.

    Although these barrier boundaries are present, the poor match to the observed data, particularly the subdued bores, suggests that the aquifer properties between the boundaries have a greater influence on drawdown than the boundaries themselves. However, this model indicates that the barrier boundaries have some influence on the drawdown, most likely the poor water level recovery after each successive pumping period in the rapid response bores. This is consistent with the current conceptual model which comprises regions where the aquifer is confined (e.g. at the borefield) and unconfined (e.g. the Barongarook High).
  - *Semi-confined*: A significant improvement in the match to the rapid response bores, particularly in the recovery data, to the one and two boundary models indicates that leakage in combination with aquifer boundaries are significant factors influencing drawdown. However, this model still results in a poor match to the subdued bores, indicating that semi-confined conditions are not the primary factor causing the small amount of drawdown in these bores.
- **Heterogeneous aquifer analysis** – The better match to the rapid response bores to the bounded models, (for confined and semi-confined aquifers) indicates that the aquifer is of limited areal extent and/or there is a large reduction in transmissivity at the location of the boundaries. However, the poor match to the subdued bores indicates that variability of aquifer transmissivity may also occur within the aquifer, rather than just a truncation of the aquifer at its natural limits).

  To examine the potential for heterogeneity in the south-west area of the model, the drawdown data was analysed using the Butler (1988) non-uniform aquifer model. This model allows prediction of drawdown in an heterogeneous confined aquifer comprising two concentric zones - an inner zone with a defined radius centred on the pumping bore, and an outer zone with an unlimited radial extent that fully encloses the inner zone. The Butler model allows Zone 1 (inner zone) and 2 (outer zone) to have different values of transmissivity and storage co-efficient, and also for the radius of Zone 1 to vary.

  Analysis was conducted for all rapid response bores and all subdued bores, and then for sub-groups of the rapid response and subdued bores. Results of this analysis are presented in Section 2.4 of the report in Appendix B. A good fit with one model for all rapid response bores and all subdued bores could not be obtained, however, very good fits could be obtained for sub-groups of the bores, e.g. when analysis used two bores from Zone 1 and the subdued bores (Zone 2). The fact that one model could not provide good fits for all bores is likely due to the limitation in the shapes allowed for the inner and outer zones (i.e. perfect circles) when in reality these zones are likely to be irregular.

The very good matches to the (paired) rapid and subdued response bores indicated that a two zone model is most representative of all the models assessed. None of the previous models could even closely match both the rapid and subdued categories of bores. Further, the review also compared the results of the Butler analytical modelling to outputs from the numerical model (for bores forming part of the calibration data-set). The Butler modelled results more closely the observed data than the numerical model. In particular, the poor calibration to the subdued response bores in the numerical model is improved with the Butler model. This suggests that the south-west boundary area of the model, or a zone between the borefield and the boundary is likely to comprise of an area of low transmissivity. The two zone model also indicates that a zone of high storage co-efficient is also a significant factor, possibly more significant than low transmissivity, influencing drawdown. (This is discussed further in Appendix B). The conceptual model on which the numerical model is based should therefore be revised.

3.1.3 Conclusions

Analysis of drawdown in observation bores located between the bore field and the model boundary indicate that there is some form of barrier to groundwater flow between the Barwon Downs and Gellibrand groundwater sub-basins. This barrier is likely to comprise two components:

- A low transmissivity zone or zones in the confined aquifer, most probably to the west of bore 64237, and

- Areas of high storage co-efficient caused by either unconfined conditions (most probably where the aquifer outcrops on the Barongarook High and to the South East of the Bambra Fault), and/or an area with high leakage rates from the aquitard.

The analysis shows clearly that the aquifer is not uniform in its hydraulic properties (i.e. transmissivity and storage co-efficient), and is likely to comprise multiple zones of varying transmissivity and storage co-efficient. Transmissivity is likely to be highest near the borefield and lowest in an area around bores 64237 and 64244 but are likely to be highly variable in size and location. The analysis does not rule out areas of high transmissivity existing in the Kawarren - Gellibrand area, as is indicated by pumping tests undertaken in that region during the Gellibrand Dam investigations in the 1970's and the Newlingrook investigations in 2007 to 2009. These variable zones of transmissivity are further supported by the flat – steep – flat pattern in groundwater gradients seen in the transition of groundwater gradients between the borefield and the Kawarren area, described in Section 2.

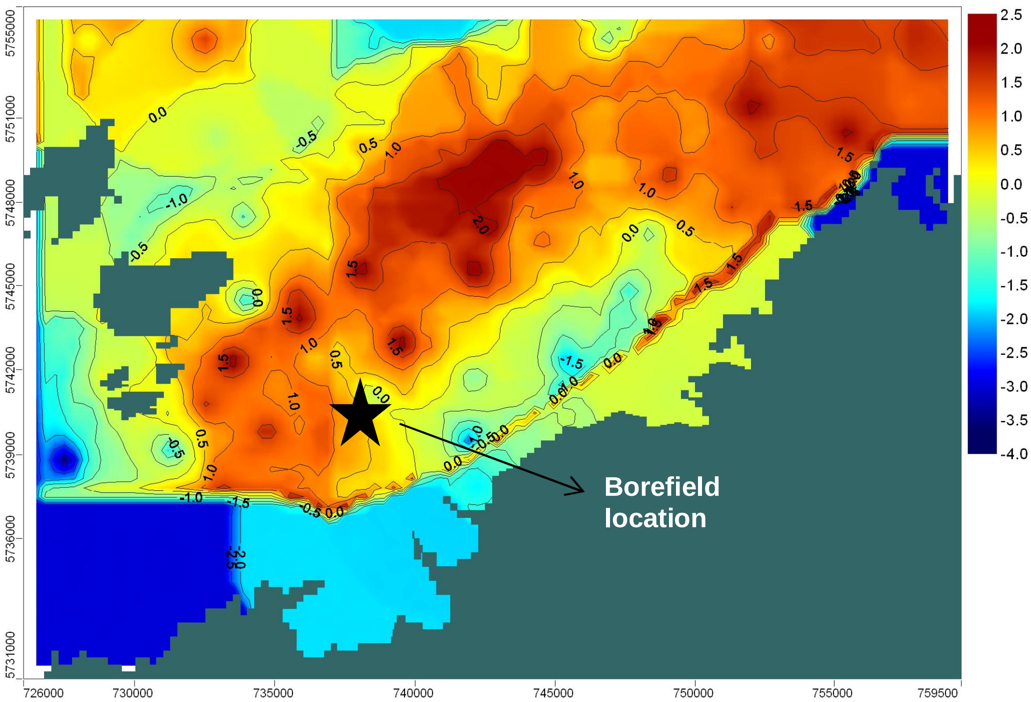
It is clear from previous investigations that the hydrogeology in the region is very complex and this is, in part, reflected in the difficulty in obtaining acceptable calibration of the existing numerical model in the south-western region. Although the analytical models used in this assessment do not fully reflect the complex hydrogeology, the good match obtained to the Butler two zone model provides a strong basis on which the conceptual model (and ultimately numerical model) should be further developed/refined.

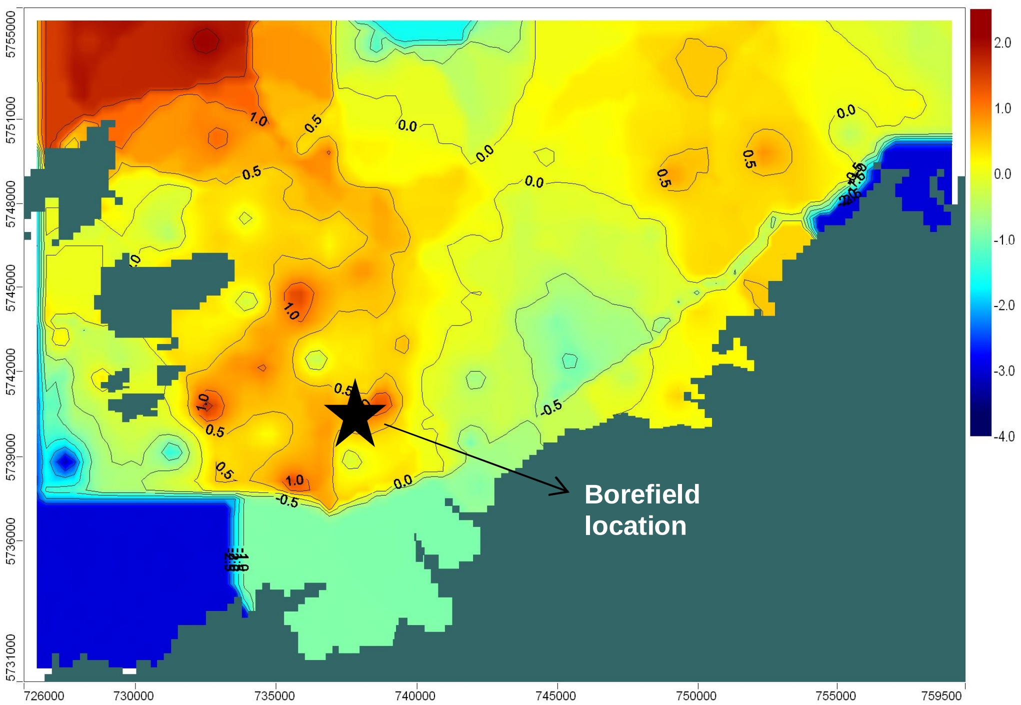
Figure 3.4 shows the distribution of hydraulic conductivity in the most recently calibrated version of the numerical model (SKM, 2011). (The upper figure is the Dilwyn Formation and the lower figure is the Pebble Point Formation). The figure shows that the model does include a zone of varying transmissivity in the LTA in the south west corner of the model. The dark blue zone in this area has a hydraulic conductivity that appears to be around 10^{-2} m/day. The boundary of this zone appears to be approximately coincident with the area where the subdued bore response starts. The poor calibration in the numerical model in the subdued bores however indicates that this conceptualisation is inadequate to represent what is occurring to groundwater levels in this area. Based on the drawdown analysis above, the following improvements to the current conceptualisation in the model should be trialled:

- Add a three zone model to represent the high-low-high transmissivity that appears to be present through this area i.e. the current model maintains a low transmissivity through the Kawarren area, where it is known that high transmissivities are present – it is more likely that the low transmissivity zone is a much narrower feature
- Vary storage properties to better reflect the influence of nearby unconfined areas on the aquifer system

- Refine the shape of the low transmissivity zone, e.g. using aquifer potentiometry (in the pre-pumping state) to better guide the boundaries of this zone.

Figure 3.4 : Horizontal hydraulic conductivity in the current Barwon Downs numerical model. Upper figure is the Dilwyn Formation (Layer 4) and the lower figure is the Pebble Point Formation (Layer 5). Units are logarithm of hydraulic conductivity, in m/day.



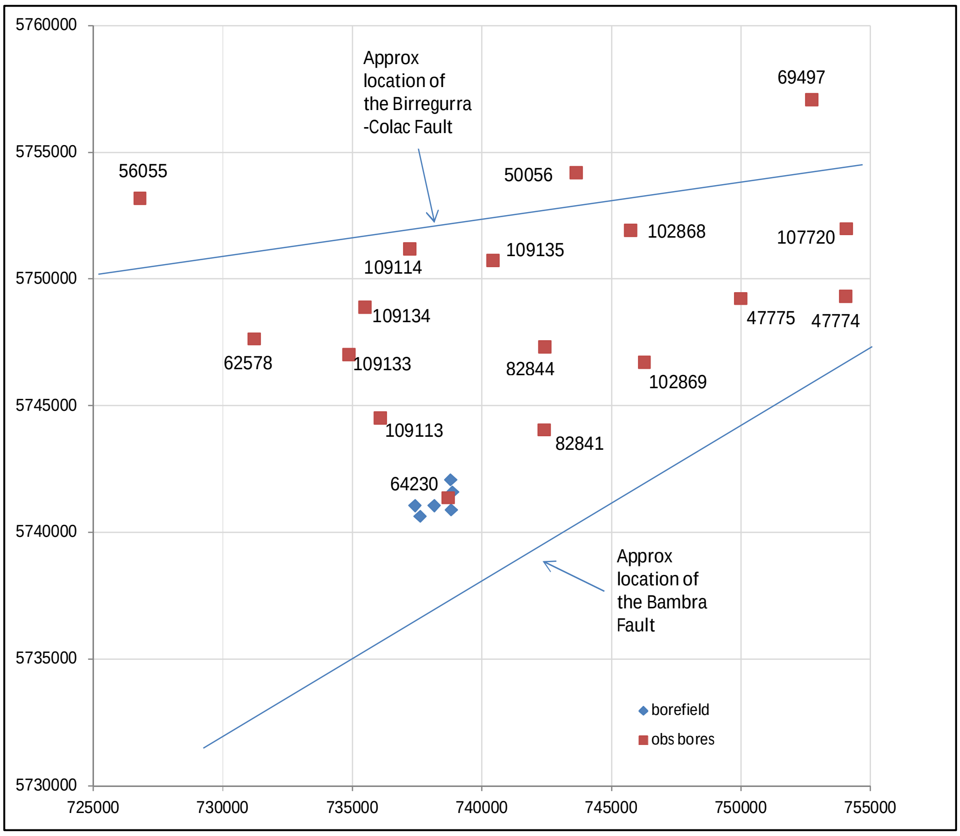


3.2 Northern area

3.2.1 Method

A total of 17 observation bores located north of the bore field were used in this analysis (refer Figure 3.5). Only three observation bores, 56055, 50056, and 69497 are located north of the fault. Bore 56055 has a continuous water level record between 1989 and 2014, whereas bores 50065 and 69497 only have water level records between 1986 and 1992, and 2000 and 2014 respectively. Drawdown cannot be calculated for bore 69497 due to the water level record commencing 13 years after the start of pumping in 1987. However, comparison of groundwater elevation with bore 56055 indicates that water levels in bore 69497 are likely to have risen since 1987 and hence, there has been no drawdown.

Figure 3.5 : Location of Lower Tertiary Aquifer observation bores used in northern area drawdown analysis



Even without the analytical analysis, it is evident from observation of the groundwater hydrographs that the fault is acting as a barrier to groundwater flow. All the observation bores on the south side of the fault display a rapid response to pumping whereas the three bores north of the fault exhibit an absence of drawdown or subdued drawdown response. This point is discussed, along with supporting hydrographs, in Section 3.2 of the report in Appendix B. Further to this, even though the hydrograph record for Bore 69497 only starts in the year 2000, its upward rising trend (3m over the period 2000 to 2014) is significant additional evidence of the strong influence of the fault.

3.2.2 Summary of results

A similar method of analysis was followed for the northern area, as per the south-west area, including initial examination of a homogenous aquifer model (for both a confined and semi-confined case), followed by a confined bounded aquifer model (trialling one and two boundaries, representing the Colac - Birregurra fault and Bambra fault) and lastly examining a two zone aquifer model.

The confined homogenous model matched well to the drawdown data, except for the final period of recovery where drawdown is under-estimated (i.e. the model shows greater recovery of water levels than actually occurred). Introducing a single boundary to the model (representing the Colac - Birregurra fault) produced a slight improvement to the model compared to the unbounded model, suggesting the faults may only be acting as partial barriers to drawdown. Other factors such as unconfined or semi-confined conditions may have a more significant impact on drawdown.

The semi-confined model with two aquifer boundaries significantly improves the match to the observed data, suggesting that leaky aquifer conditions in combination with aquifer boundaries are key contributors to the observed drawdown. To examine the potential for unconfined regions to influence drawdown (and hence, be more significant than aquifer boundaries) an analysis using the Butler model was also undertaken – these results produced a very good match to the observed data, which was slightly better than that produced by the semi-confined two boundaries model. The Butler model results in an inner zone with transmissivity and storage coefficient very similar to the confined unbounded model with a radius of 24 km (approximate distance to the Colac-Birregurra Fault is 15 to 25 km), surrounded by an outer zone with a lower transmissivity.

The Butler and the semi-confined bounded models indicate that leakage is required to provide a good match to the observed data. The Butler model allows leakage from a zone of lower transmissivity (at distance from the borefield) whereas the semi-confined model provides leakage from the aquitard.

Considering the combined information sources of the distance drawdown data, drawdown maps, and aquifer analysis, the review concludes that the Colac-Birregurra Fault is unlikely to act as a no flow boundary as is currently employed in the numerical model. Not allowing some leakage across the fault may result in higher aquitard Kv values, too high values of transmissivity, or increased specific yield in the unconfined regions of the model.

The mdGroundwater (2014) review concludes that while the relatively poor fit to the last period of recovery may be a result of an aquifer boundary, this is unlikely due to the Colac –Birregurra and/or Bambra Faults, as the analysis suggests that such a boundary would need to be a much greater distance from the borefield than either of these features in order to explain the recovery curves. Other possible explanations raised in the report for the slow recovery is the proximity to the Barongarook High unconfined area (presumably for bores in the western part of the analysed area) and lower transmissivity in the north-west direction (presumably for bores in the eastern part of the analysed area). (Note that there is no evidence one way or another for lower transmissivity in the north-west direction).

Comparison of the Butler two zone model predicted water levels compared to the numerical model showed the two zone model to provide a better fit to observed drawdown.

3.2.3 Conclusions

Analysis of drawdown in observation bores located between the bore field and the Colac-Birregurra Fault indicate that the fault is unlikely to act as a no-flow boundary. However, it is likely that there is a significant reduction in transmissivity, possibly as high as 90%, on the north side of the fault.

Given that the Colac-Birregurra fault is represented as a no-flow boundary in the numerical model and drawdown in the numerical model is generally less than the observed data tends to suggest that the transmissivity in the numerical model is too high, and/or the storage co-efficient or aquitard leakage is too high.

3.3 Estimation of aquifer transmissivity from lithological data

Lithological logs for the bores used in the drawdown analysis (i.e. the prior sections in this chapter) were analysed to estimate the transmissivity based on the recorded lithology. The section of the log used in the transmissivity section was the LTA aquifer thickness as identified in the Victorian Stratigraphic Database. Lithological data was been simplified on the basis that sands and gravels were assigned a K of 1 m/day, and clays and marls were assumed to be 0 m/day. For the variety of lithological descriptions in between these end members, the following proportions of 'aquifer' and 'aquitard' material were assumed:

Logged lithology	Assumed aquitard	Assumed aquifer
Sand	0%	100%
Clay	100%	0%
Sand and Gravel	0%	100%
Gravel	0%	100%
Sand and Clay	50%	50%
Sandy clay	90%	10%
Gravel , sand and clay	50%	50%
Pyrites		
Carbonaceous		
Limestone	0%	100%
Sand and Marl	50%	50%
Marl	100%	0%
Sandy Marl	90%	10%
Sandstone and clay	50%	50%
Siltstone	100%	
Sand and siltstone	50%	50%
Mudstone	100%	0%

For example, a sandy clay was assumed to comprise 90% 'aquitard' material and 10% 'aquifer' material, meaning that it was effectively assigned a hydraulic conductivity of 0.1 m/day. On this basis the thickness of each lithological interval can be multiplied by the assumed hydraulic conductivity to give a corresponding transmissivity. The transmissivities are then summed to give the overall transmissivity for each bore.

3.3.1 South western area

The results of the lithological analysis in the south western part of the study area are shown in Table 3.1. (Bore 64240 was not included as it does not have a stratigraphic interpretation, and 64227 was not included as it does not have a lithological log). The rapid response bores are plotted at the top of this table (shaded grey). The drawdown analysis hypothesises a higher transmissivity zone for the rapid response bores. However, this is not supported by the results of the analysis presented in Table 3.1, with those bores not showing a consistently higher predicted transmissivity for the LTA compared to the subdued response bores. This does not mean however that the hypotheses from the drawdown analysis is wrong. There are a number of reasons why this analysis could be a poor predictor of LTA transmissivity:

- The most important is that there is insufficient detail in the lithological logs to provide an accurate break down of the actual lithology e.g. for sequences described as "clays and sands" we have assumed a 50% split when the reality could be very different. More importantly, even if the major lithological categories were defined accurately, the importance of defining a fine sand versus a coarse sand is critical in terms of the hydraulic properties of the aquifer, but the lithology logs do not contain this detail.
- A further potentially important limitation is that it doesn't take structure (i.e. layering) into account. For example, if a bore is screened in a sandy layer but is separated from the pumped unit by clay layers then the method breaks down. Structure can have a very large impact on water level response, particularly if a bore is screened above/below a major clay layer.

- Estimating transmissivity from lithology, even when the lithology is accurately known, is an inaccurate science and usually contains significant error. This is because other factors apart from lithology can be important such as the way sediments are packed and laid down, the role of very thin high permeability zones or fractures which are not discernible in the lithology logs.
- The assumed LTA thickness is derived from stratigraphic data (which has not been reviewed as part of this assessment) and the actual/effective LTA thickness may not be accurately captured by the stratigraphic breakdown.

While the results do not provide clear support for the two-zone model of higher and lower permeability for the rapid and subdued response bores respectively, there are hints in the data that this method is worth pursuing further, e.g. two of the rapid response bores contained the highest percentage of higher permeability strata (74% and 78%), and four of the six subdued response bores contain the lowest percentage of higher permeability strata (26% to 35%) in the table.

As described above, the greatest limitation with this method is the poor quality of the lithological information. Further, if more accurate lithological information was available, then a more sophisticated hydraulic conductivity model could be applied (instead of simply two categories for aquifer and non-aquifer material). Also, to warrant pursuing further, the method would need to take account of aquifer structure and associated vertical variations in lithology.

To further advance this approach, and more importantly to support development of improved hydrostratigraphic layers in the numerical model, gamma logging of the key bores in this area is recommended (for at least the ten bores in the drawdown analysis). While gamma logs do not provide a lithological description as such, they provide a good indication of the clay content of sediments, which is a key factor influencing the permeability of unconsolidated aquifer sediments.

Table 3.1: Predicted transmissivity based on lithological analysis of Lower Tertiary Aquifer – south western model boundary

Bore ID	Thickness of Lower Tertiary Aquifer (m) (1)	Percentage of higher permeability (e.g. sandy) strata	Predicted transmissivity (m^2/day)
64236	107	38%	40
64237	19	74%	15
64229	160	78%	125
64227	97	52%	50
108914	51	35%	20
64244	34	29%	10
108911	146	53%	80
108915	68	29%	20
48003	89	26%	25

Notes:

1. Thickness from Victorian Stratigraphic Database
2. Shaded rows are the ‘rapid response bores’

3.3.2 Northern area

Using the same method outlined above, bores in the northern area have been assessed to estimate a transmissivity from the lithological data. At the northern boundary the bores have been separated based on their location in relation to the Birregurra-Colac Fault to assess whether those bores to the north of the fault show a different response due to lower hydraulic conductivity zone or due to another explanation such as the presence of the fault. The results of the lithological analysis are shown in Table 3.2 and do appear to show a lower predicted transmissivity than those bores to the south of the fault. The bores to the north of the fault also indicate a smaller aquifer thickness, which contributes to the low predicted transmissivity values.

The fact that this approach highlighted a significant difference in transmissivity between the two areas of interest, compared to the south-west area, reflects the more distinct boundary (i.e. a fault with a large offset) separating the areas in the north. The transmissivity differences are more controlled by differences in thickness, rather than lithology.

Table 3.2 : Predicted transmissivity based on lithological analysis of Lower Tertiary Aquifer – northern model boundary

Bore ID	Thickness of Lower Tertiary Aquifer (m) (1)	Percentage of higher permeability (e.g. sandy) strata)	Predicted transmissivity (m^2/day)
56055	4	100%	5
50056	40	23%	10
69497	12	49%	5
102868	223	64%	140
109114	126	45%	60
109134	32	54%	20
107720	155	54%	80
62578	63	27%	15

Notes:

1. Thickness from Victorian Stratigraphic Database
2. Shaded rows are those bores to the north of the Birregurra-Colac Fault

4. Review of need for stream gauges in upper Gellibrand catchments

The primary purpose of this report was not to predict potential impacts of Barwon Downs pumping in the Gellibrand catchment. However, part of the study involved recommending whether additional stream gauges are required in the upper Gellibrand catchment area. The analysis described in previous sections of this report suggest that any impact on the Gellibrand groundwater system will be small due to the effect of a hydraulic restriction within the aquifer between the Barwon and Gellibrand catchments. However, to address this issue in a more quantitative manner an analytical assessment of drawdown was undertaken and is described below.

The assessment involved matching the drawdown observed in the pumped aquifer in the upper Gellibrand area (of around 3 metres) using the two layer analytical solution of Boulton (1963) with a semi-confined pumped aquifer overlain by an aquitard. The analysis involved inputting average borefield pumping rates since commencement of extraction to estimate drawdown in the overlying aquitard. The following input parameters were used in the analysis:

- Aquifer transmissivity: 400 m^2/day
- Storage coefficient of the pumped aquifer: 0.0005
- Vertical permeability (hydraulic conductivity) of the aquitard: 0.00005 m/d
- Thickness of the aquitard: 150 m
- Specific yield of the watertable aquifer: 0.2
- Average pumping rate: 7 ML/day (assumes continuous pumping)
- Distance from borefield: 13,000m

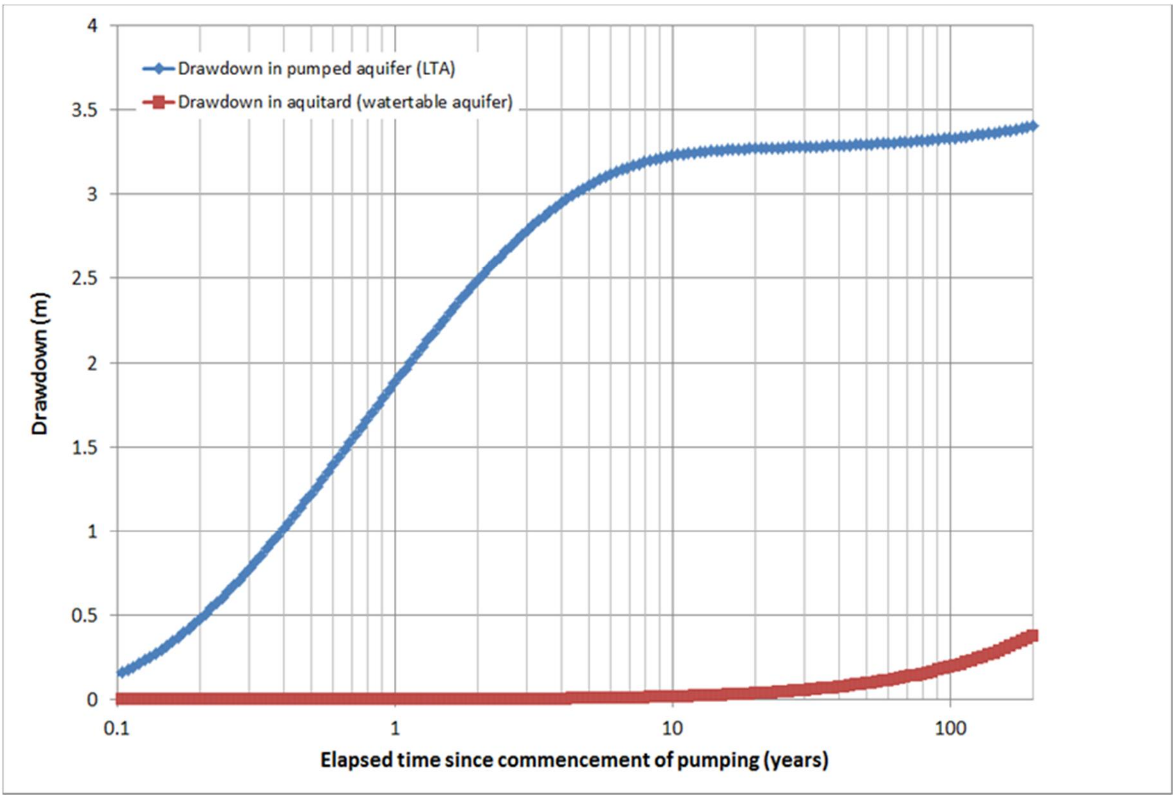
The results are presented in Figure 4.1 and show a predicted drawdown in the aquitard of less than 50cm over the long term. It is recognised that using this method (of matching the drawdown to that observed in the pumped aquifer) is not a unique solution. However the input parameters used are based on the best available information, and the resulting drawdown in the aquifer is approximately as observed after the current period of borefield operation (i.e. around 30 years).

Hence while there are a number of assumptions embedded in the analysis, the results appear reasonable. Further, a more detailed analysis will be undertaken leading up to licence renewal using the re-calibrated numerical model. Together with the other findings of this report, it is concluded that groundwater drawdown in the watertable in the Gellibrand Catchment (in particular Porcupine Creek) is likely to be small to negligible. Therefore installation of additional stream gauges in this area is not recommended. This does not preclude installation of gauges at some stage in the future, and indeed the analysis presented in this section shows that the timeframes of change in the watertable (in the aquitard) are very long, and hence there is no urgent need for stream gauge installation.

The above analysis relates to potential drawdown in the aquitard in the south-west area and hence is relevant to streams such as Porcupine Creek and Love Creek. An additional and related issue is the potential for impacts where the aquifer outcrops in the Gellibrand catchment, in particular Ten Mile Creek and Yahoo Creek. Drawdown mapping indicates that drawdown in these areas in 2012 (representing the time period of approximate maximum historical drawdown in the unconfined part of the aquifer at distance from the borefield) is less than one metre. In Jacob's opinion the likelihood of any significant impacts on streamflow is considered to be low for these creeks. As such, installation of additional stream gauges for these creeks is not recommended. As described above, a more detailed analysis of any potential impacts on these creeks will be undertaken using the re-calibrated numerical model. However, this review does not preclude installation of stream gauges at some stage in the future.
Ten Mile Creek does have some periods of historical flow record (e.g. as measured during 2009-10) as part of the Newlingrook groundwater investigation, which will be useful data in the model calibration process. Further,

as part of the tree water use study (report in progress), a new shallow monitoring bore was recently installed adjacent Ten Mile Creek (at the intersection of Cashins Rd and Robinsons Rd). This bore will also be important in the calibration of the numerical model in the vicinity of Ten Mile Creek.

Figure 4.1 : Estimated drawdown in the watertable in the upper Gellibrand catchment (using Boulton 1963)



5. Conclusions

5.1 Elevation and thickness of LTA and bedrock

The purpose of the review of aquifer thickness and extent was to evaluate whether the aquifer around the boundaries of the current numerical model is sufficiently well defined in the southwest and northern areas. In the south west area, the review found that:

- The current numerical model does not match well with stratigraphic interpretation in terms of aquifer thickness (most probably due to changes in stratigraphic interpretation since the model was first constructed). The review suggests that the current numerical model layers need to be revised in the south west and northern areas. Further, the review indicates that the Newlingrook model is a much better fit to the stratigraphic data in terms of LTA thickness and would be a logical starting place in reconstructing the model layers.
- In terms of bedrock (basement) elevation, the Newlingrook Model also most closely represents the available stratigraphic information. The bedrock elevation of the current numerical model does not match well with the stratigraphic information; 50% of bores in the current model area show more than a 20m difference in elevation and one third show more than a 40m difference. In the south-west corner of the model, the elevation of the bedrock in the numerical model is too high - the Newlingrook model has the bedrock elevation generally 10 to 100m lower through this area compared to the current numerical model.
- In terms of LTA elevation, the difference between the Newlingrook Model and the Barwon Downs model are not as significant as the LTA thickness and bedrock elevation. Again, the Newlingrook Model is a better representation of the available stratigraphic information in the south western area, however the differences are smaller in magnitude.
- The monocline that has been included in the Newlingrook model is a significant difference between the two models in the south west area. The inclusion of this feature in the structure of a new model is recommended, however the extent to which the interpretation of Bore 64235 has been used as a basis for the geometry (particularly the steepness) of the monocline should be reviewed. The interpretation of the bedrock in the base of Bore 64235 is considered to be erroneous. Correcting the interpretation in this bore will also remove the area of LTA that is currently interpreted as being unsaturated.
- The representation of unsaturated LTA (i.e. where the watertable resides in the bedrock) in the current numerical model needs to be reviewed. The bedrock is a no-flow boundary in the current numerical model and given that bedrock outcrops in the middle portion of Boundary Creek, and hence is an important area of interest, the no-flow boundary may not be the most appropriate boundary condition.
- Layering within the aquifer is currently based on stratigraphy alone. This can bias the conceptualisation (as has been demonstrated by recent lithological cross-sections prepared for the Barongarook High area, which revealed the aquifer to comprise confined and unconfined regions within the Barongarook High) and revision of the layering based on lithology should be considered (at least within the LTA, not the aquitards).

In summary, this review of aquifer thickness and extent in the south east area did not identify anything particularly conspicuous that would account for the marked change in drawdown behaviour that is observed between the Barwon and Gellibrand catchment, such as dramatic thinning of the aquifer or unsaturated zones / zones of absent aquifer. Clay layers and/or pinching out of sand layers within the aquifer could however explain this (and the elevation of observation bore screens in relation to these layers), and this will need to be assessed as part of the conceptualisation process. The review did find however that in general the current layers within the model do not match the aquifer geometry as well as the stratigraphic information suggests they could, and that the Newlingrook model is a better representation of this part of the study area. While these differences are unlikely to be the main reason for the poor calibration in this area, improving the aquifer geometry in the model so that it is a closer fit to actual data is likely to contribute to a better calibration.

In the northern area it was found that there are no significant discrepancies between the current Barwon Downs model and the Newlingrook model or between the current Barwon Downs model and the stratigraphic information, suggesting that there is no real improvement to be made to the model layers in this area based on the available bore data. However, there are differences between the interpretation between bores in the Barwon

Downs model and the Newlingrook model and that these differences should be investigated to determine the rationale and suitability of the Newlingrook interpretation. Also, the numerical model should be expanded to include four additional bores (three north of the fault and one south): 56055, 50056, 109114 and 69497.

In the north east corner of the model this review found that there is a significant difference between the Newlingrook and the numerical model layers. The Newlingrook model suggests that the LTA is deeper and the aquitard thicker than used in the numerical model. This is supported by the stratigraphic and lithological logs. The implication is that the risk of watertable drawdown (and associated risks such as activation of PASS) is likely to be significantly overstated by the current numerical model.

5.2 Review of aquifer potentiometry

In the natural (pre-pumping) condition, the location of the groundwater divide between the Barwon and Gellibrand groundwater catchments is not coincident with the surface water divide (as previously conceptualised) but is located between 2 - 5 km further north-east, into the Barwon catchment. The significance of this is that it is not the groundwater divide which ‘protects’ or prevents any impacts from the borefield pumping reaching the Gellibrand River. Rather it is the (postulated) change in hydraulic properties which acts as the “boundary” between these two catchments. (Groundwater divides are not like surface water catchment divides and move naturally due to changes in seasonal or long term recharge rates - because they are not a static boundary a groundwater divide is not a barrier that prevents impacts from reaching beyond a divide).

The groundwater gradient in the Barongarook High outcrop (unconfined) areas is generally relatively steep but in the northern and Barwon groundwater catchments this gives way to much flatter gradients as the aquifer transitions to confined conditions, indicative of relatively higher transmissivity. In contrast, in the ‘Gellibrand’ groundwater catchment the groundwater gradient in the transition to the confined aquifer is characterised by a continuation of the steep gradients. These steep gradients coincide with the transition to the area where subdued responses (to groundwater pumping) are observed in the monitoring bores and are indicative of some type of change in the aquifer through this area, such as lower transmissivity.

This review also found that the extent of the unsaturated area of aquifer in the Barongarook High area is overestimated and should be corrected by incorporating information on bedrock elevation from the 2014 bores into the aquifer geometry.

Under the effect of pumping – as seen in the difference between the 1987 and 2012 contours - the groundwater divide separating the Barwon and Gellibrand groundwater catchments has subsided (in the confined part of the aquifer), and the two catchments are merged into one large groundwater catchment, where groundwater flows in a south westerly direction. There is a new catchment divide which has been established that sits approximately between Birregurra and Deans Marsh. However, groundwater gradients towards the Gellibrand River are essentially unchanged, meaning that the change in groundwater discharge to the Gellibrand River will be very small.

Recovery of groundwater levels between 2012 and 2014 results in the re-establishment of the groundwater divide between the Gellibrand and Barwon groundwater catchments, although it is between 2-4km to the south-west of the pre-pumping divide. For the 2014 surface there are now four main groundwater catchments, with the ‘new’ catchment being the borefield catchment, where regional groundwater flow direction is towards the borefield. As levels near the borefield further recover, the groundwater catchment divide between the Barwon catchment and the borefield will disappear and the three main catchments, as per the pre-pumping case, will be re-established.

Examining how groundwater divides and flow patterns have changed under the influence of pumping is of interest and helps in some way in the conceptualisation of the groundwater system, it can also be misleading in that it is not an accurate guide to potential impacts of the borefield. What is most important is considering how groundwater pumping has changed groundwater flux (i.e. rate of discharge) to receptors of significance (e.g. the Gellibrand River). While the potentiometric data shows that the groundwater divide between the Barwon and Gellibrand subsides between 1987 and 2012 (in the confined part of the aquifer) this does not necessarily mean a significant impact on the Gellibrand River has occurred. Indeed, evidence such as groundwater gradients near the river suggest that any impact is likely to have been very small. However, this would need to be confirmed via a numerical model.

5.3 Drawdown analysis

South West Area

Analysis of drawdown in observation bores located between the bore field and the model boundary indicate that there is some form of barrier to groundwater flow between the Barwon Downs and Gellibrand groundwater sub-basins. This barrier is likely to comprise two components:

- A low transmissivity zone or zones in the confined aquifer, most probably to the west of bore 64237, and
- Areas of high storage co-efficient caused by either unconfined conditions (most probably where the aquifer outcrops on the Barongarook High and to the South East of the Bambra Fault), and/or an area with high leakage rates from the aquitard.

The analysis shows clearly that the aquifer is not uniform in its hydraulic properties (i.e. transmissivity and storage co-efficient), and is likely to comprise multiple zones of varying transmissivity and storage co-efficient. A good matches to both the rapid and subdued response bores in the south west area could only be obtained using a two zone aquifer model - transmissivity is likely to be highest near the borefield and lowest in an area around bores 64237 and 64244 but are likely to be highly variable in size and location.

The analysis does not rule out areas of high transmissivity existing in the Kawarren - Gellibrand area, as is indicated by pumping tests undertaken in that region during the 1970's and 1980s, and the Newlingrook investigations in 2007 to 2009. These variable zones of transmissivity are further supported by the flat – steep – flat pattern seen in groundwater gradients.

It is clear from previous investigations that the hydrogeology in the region is very complex and this is, in part, reflected in the difficulty in obtaining acceptable calibration of the existing numerical model in the south-western region. Although the analytical models used in this assessment do not fully reflect the complex hydrogeology, the good match obtained to the Butler two zone model provides a strong basis on which the conceptual model (and ultimately numerical model) should be further developed/refined.

While the most recently calibrated version of the numerical model (SKM, 2011) does include a zone of varying transmissivity in the LTA in the south west corner of the model, the poor calibration in the numerical model in the subdued bores indicates that this conceptualisation is still inadequate to represent what is occurring to groundwater levels in this area. The report contains a number of suggestions as to how this area of the model could be improved.

Northern boundary

Considering the combined information sources of the distance drawdown data, drawdown maps, and aquifer analysis, the Colac-Birregurra Fault is unlikely to act as a no flow boundary as is currently employed in the numerical model. However, it is likely that there is a significant reduction in transmissivity, possibly as high as 90%, on the north side of the fault. Given that the Colac-Birregurra fault is represented as a no-flow boundary in the numerical model and drawdown in the numerical model is generally less than indicated by the observed data, tends to suggest that the transmissivity in the numerical model is too high, and/or the storage co-efficient or aquitard leakage is too high .

Estimation of aquifer transmissivity from lithological data

Lithological logs for the bores used in the drawdown analysis were analysed to estimate the transmissivity based on the recorded lithology. The drawdown analysis hypothesises a higher transmissivity zone for the rapid response bores. However, this is not supported by the results of the analysis, i.e. the rapid response bores did not showing a consistently higher transmissivity for the LTA compared to the subdued response bores. This does not mean however that the hypotheses is wrong. A significant limitation with the method is that there is insufficient detail in the lithological logs to provide an accurate break down of the lithology. To further advance this approach, and more importantly to support development of improved hydrostratigraphic layers in the numerical model, gamma logging of the key bores in this area is recommended (for at least the ten bores in the drawdown analysis). A further limitation is that the approach doesn't take structure (i.e. layering) into account. Structure can have a very large impact on water level response, particularly if a bore is screened above/below a major clay layer. This lends further support to the suggestion that revision of the layering in the updated numerical model should consider including lithology (at least within the LTA) and not stratigraphy alone.

Bores in the northern area were assessed to estimate a transmissivity from the lithological data. The results of the lithological prediction of transmissivity do support a lower predicted transmissivity than those bores to the south of the fault, although this is primarily driven by a thinner aquifer, rather than lower permeability sediments.

5.4 Summary

The overarching objective of this review was to ensure that any limitations in the hydrogeological conceptual understanding of these two areas are identified, and that recommendations to address these limitations are made. The sub-objectives of this study are revisited below along with an assessment of how this study has addressed the objectives:

1) *Identify the potential for the south west area to act as a barrier or partial barrier (i.e. restriction) to groundwater flow between the Barwon Downs and Gellibrand groundwater sub basins* – This review has identified that there is some form of barrier to groundwater flow between the Barwon Downs and Gellibrand groundwater sub-basins, and that the barrier is likely to comprise a low transmissivity zone or zones in the confined aquifer, and areas of high storage co-efficient caused by either unconfined conditions and/or an area with high leakage rates from the aquitard.
2) *Identify the potential for the Birregurra and Colac Faults to act as a barrier to north-south groundwater flow* - The Colac-Birregurra Fault is unlikely to act as a no flow boundary as is currently employed in the numerical model. However, it is likely that there is a significant reduction in transmissivity across the fault.
3) *Identify any unusual or unexplained characteristics that may require further investigation (and/or modification to the drilling program)*
    a) The cause of the low transmissivity in the subdued response bores is not well understood (e.g. is not evidently apparent based on average transmissivity estimated from lithology logs) and should be further investigated (e.g. via gamma logging of the bores and via consideration of layering within the LTA and screening of bores relative to those layers).
    b) Investigation of the 'subdued response' bores should also consider revising the layers in the numerical model so that lithology is used to define layers within the aquifer, rather than only using stratigraphy to define layers.
    c) The revised interpretation in the NE part of the model should be confirmed, given the implications for watertable drawdown in this area
    d) The cause/s of drawdown in the bores around Kawarren investigated further, given that bore 48003 (which is closer to the borefield) displays significantly less drawdown. This review could also investigate whether the drawdown in 48003 is anomalous (i.e. rather than the bores near Kawarren being anomalous)
4) *Identify alternative bore locations and/or depths of proposed drilling program (if any)* – No new bores are recommended from this program.
5) *Compare review outcomes against current groundwater model and identify changes that may be required to ensure the model adequately represents the conceptual model:*
    a) The aquifer structure in the south-west corner of the model needs to be amended, using the Newlingrook model as a starting point
    b) The aquifer structure in the north-east corner of the model needs to be revised, again using the Newlingrook model as a starting point

c) The no-flow boundary condition imposed on the Colac-Birregurra fault should be removed, and replaced with a boundary that represents a significant reduction in hydraulic connection (e.g. large reduction in transmissivity across the fault).

d) The numerical model boundaries need to be significantly expanded, approximately as far as Gellibrand in the south-west corner, to include bore 56055 in the north-west corner along with the other two bores described in the northern drawdown analysis and by at least 2-3 km in the north-east corner (as drawdown analysis indicates the drawdown cone, at its peak) will unduly interact with boundaries in that direction.

6. Recommendations

This report makes the following recommendations:

1. The aquifer and bedrock structure of the current numerical model needs to be refined, using the Newlingrook model as a starting point

2. Due to the highly complex nature of the hydrogeology in the project, area refinement of the conceptual model (for the entire model area or where the numerical model calibrates poorly with observed data) should be undertaken before any attempt is made to refine the current numerical or build a new numerical model. A suggested approach is outlined in Section 2.5 and 3.5 of the report in Appendix B. This approach is based around slowly adding complexity to an initially simple model.

3. The numerical model boundaries need to be expanded, to approximately Gellibrand in the south-west corner, touching the southern edge of Lake Colac to the north and expanding 2-3 km to eastward.

4. The way the Colac-Birregurra Fault is represented in the model should be reviewed and a more appropriate boundary employed that allows for flux across the fault. Initial settings during model calibration should allow for no resistance to flow, and then reduced until a satisfactory calibration is obtained. An alternative approach would be to include a zone of low transmissivity aquifer on the north side of the fault and include observation bores 56055 and 69497 for model calibration.

5. The cause of the low transmissivity in the “subdued response” bores is not well understood and should be further investigated. Gamma logging of the bores is recommended as a first step. This should also include some of the “rapid response” bores for comparison. Gamma logging existing bores, if not available, would be a cost effective method of obtaining high quality information on aquifer and aquitard lithology. This would be particularly useful in identifying structure within the aquifer and the aquitard, which could significantly improve understanding on the potential for semi-confined conditions to be present, and whether the aquifer should be considered to be a single unit or divided into sub-units.

6. Attempts be made to obtain groundwater level data from private bores 50057 and 50061 (which are in close proximity to observation bore 50056) to better determine current groundwater level on the north side of the Colac-Birregurra fault. This would significantly reduce uncertainty regarding drawdown transmission across the fault. If historical data could also be found then this could be analysed using methods similar to those applied in this assessment to evaluate the degree of transmissivity reduction across the fault.

7. The cause/s of drawdown in the bores around Kawarren investigated further, including examining the likely magnitude of groundwater pumping in the area. The review should also investigate whether there is any reason to suspect that the drawdown in 48003 is other than reliable.

8. The drawdown analysis method be employed to examine the nature of the Bambra fault boundary, i.e. the southern and south-east boundary of the numerical model. Groundwater flow across the Bambra Fault is also a significant component of the current conceptual model and could have some bearing on how the south-west model boundary is conceptualised. An analysis of leakage across this fault (to the north and south of the bore field) using methods similar to those applied in this report would assist significantly in the development of the conceptual model.

9. Following on from the above recommendation, a review of paired bores (bores in close proximity to each other) on either side of the Bambra fault should be conducted. At some of these paired sites, there is likely to be value in installing data loggers in these bores (at least on a temporary basis in order to provide data for upcoming recalibration of numerical model).

7. References

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Appendix A. Stratigraphic information within the study area


Barwon Water Authority
Barwon Downs Groundwater Model
LOWER TERTIARY THICKNESS
DIFFERENCE AS PERCENTAGE
OF MODFLOW THICKNESS
Kilometres
0 0.5 1 2 3
new_strat point
newlingrook point
MODFLOW model domain
Basement
Difference (%)
Newlingrook GREATER THAN MODFLOW model
> 500
500 - 100
100 - 50
50 - 20
Newlingrook LESS THAN MODFLOW model
< 20
20 - 50
50 - 100
> 100
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Disclaimer: Topography
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JACOBS SKM
I:\VWES\Projects\VW07373\Technical\VW0XXXX\Spatial\Working\lta_iso_diff_percentage.mxd
WEST BARWON RESERVOIR

Appendix B. Drawdown analysis report

Jacobs SKM

Barwon Downs Hydrogeological Conceptual Model

Analysis of drawdown to refine conceptual model at the SW and NE Barwon Downs numerical model boundaries

FINAL 1

11 December 2014

mdGroundwater

author: Mike Dudding

ABN 75 940 815 281

Contents

1 Introduction

1.1 Background

The Barwon Downs bore field is operated under licence from Southern Rural Water. This licence was granted in 2004 after an extensive review process involving an expert advisory panel which considered potential impacts and conditions required for the new licence. This licence is due to expire in June, 2019.

A review of flora and groundwater levels completed under licence conditions(SKM and EA, 2008-09) recommended that a long term vegetation and hydrogeological monitoring program be designed and implemented to better understand a range of factors (such as groundwater extraction, drought and land use changes) that may be contributing to the drying of the catchment.

The Barwon Downs licence renewal process comprises four stages, with Stage 1 currently in progress. The Desk Top Study (Stage 1, Task B) identified potential gaps in the hydrogeological conceptual model and made recommendations on how these gaps should be addressed. One of those recommendations was to use existing data to evaluate whether the aquifer around the model boundaries is sufficiently well defined in the following two areas:

- South-west boundary (ie the boundary between the Barwon Downs and Gellibrand groundwater sub-basins, and
- North east boundary (ie Birregurra and Colac faults, and postulated Barongarook Creek Fault

Although it was considered unnecessary to undertake on site investigations in these two areas, it was considered prudent that the desk based data review be conducted in a time frame that would enable any significant gaps/issues identified in the review to be incorporated into the Stage 2 program before it is completed. A timely review will ensure there are no potentially significant impacts on the numerical modelling outcomes.

1.2 Obectives

The objectives of the review are as follows:

1. Identify potential for the south west area to act as a barrier or partial barrier (i.e. restriction) to groundwater flow between the Barwon Downs and Gellibrand groundwater sub-basins

2. Identify potential for the Birregurra and Colac Faults to act as a barrier to North-South groundwater flow

3. Identify any unusual or unexplained characteristics that may require further investigation (and/or modification to the proposed drilling program)

4. Identify alternative bore locations and/or depths of proposed drilling program (if any)

5. Compare review outcomes against current groundwater model and identify changes that may be required to ensure the model adequately represents the conceptual model (NOTE: this should be considered a first step in the refinement of the conceptual model, because more data will be

obtained at a later date from Stage 2, and during re-calibration of the refined groundwater model in Stage 3).

To achieve the project objectives an analysis of bore logs and drawdown were undertaken. This report describes the drawdown analysis component (Task D) of the project.

NOTE:

- It is not the objective of this report to assess aquifer hydraulic properties, even though hydraulic values are produced using the methods applied in this assessment
- Drawdown is calculated from the start of first main period of pumping which commenced in March 1987. Drawdown during short periods of pumping during the construction of the bore field prior to 1987 would have fully recovered before the March 1987 and, hence, not impact on this analysis.
- It has been assumed that the Dilwyn, Mepunga, Pebble Point formations form a single aquifer (ie there are no aquitards between these units) because all three units are intersected and pumped by the bore field.
- Due to the long periods of pumping used in this analysis, groundwater flow within the aquifers will be predominantly horizontal (ie parallel to the aquifer bedding). As a result, the aquifer the vertical hydraulic conductivity will have limited influence on groundwater flow so has assumed to be the same as the horizontal hydraulic conductivity (ie Kh/Kv ratio for the aquifer has been assumed to be 1).
- Drawdown used in this analysis has not been adjusted for any long term groundwater trends due to non-pumping effects, such as drought. The significance of ‘drawdown’ due to drought on the analysis is evaluated in Section 4 of this report.

2 South West Boundary

2.1 Observation bores

A total ten observation bores monitoring the Lower Tertiary Aquifer in the area between the bore field and the south western margin of the model domain were selected for this analysis (Figure 1). These bores were selected due to their relatively long monitoring record that commenced prior to or at the same time bore field operation commenced, and their location between the bore field and the Gellibrand sub-catchment. The water levels from these observation bores have been converted to drawdown after commencement of pumping. Drawdown prior to the start of pumping has not been shown (Figure 2).

Figure 1: Location of Lower Tertiary Aquifer observation bores used in this report, and Lower Tertiary Aquifer thickness (modified after SKM document I:\VWES\Projects\VW04085\Technical\spatial\gw_model\spatial\arcmap\lta_iso.mxd)

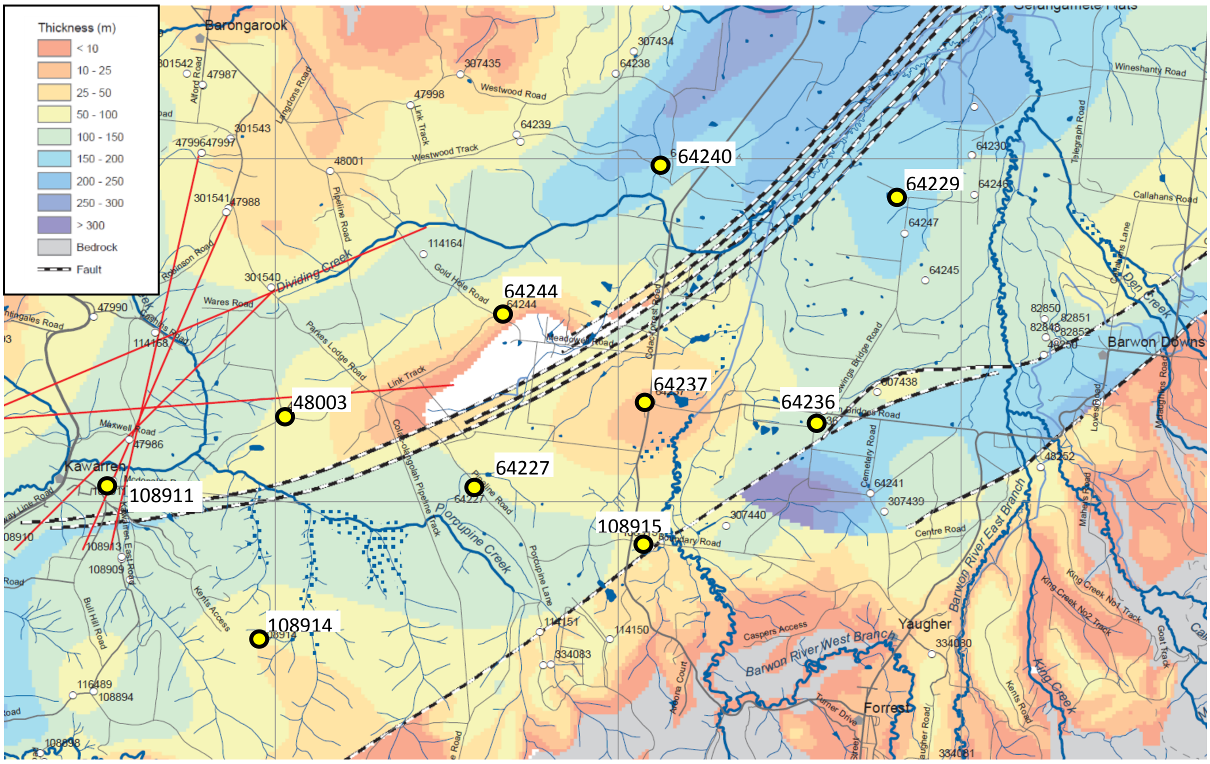
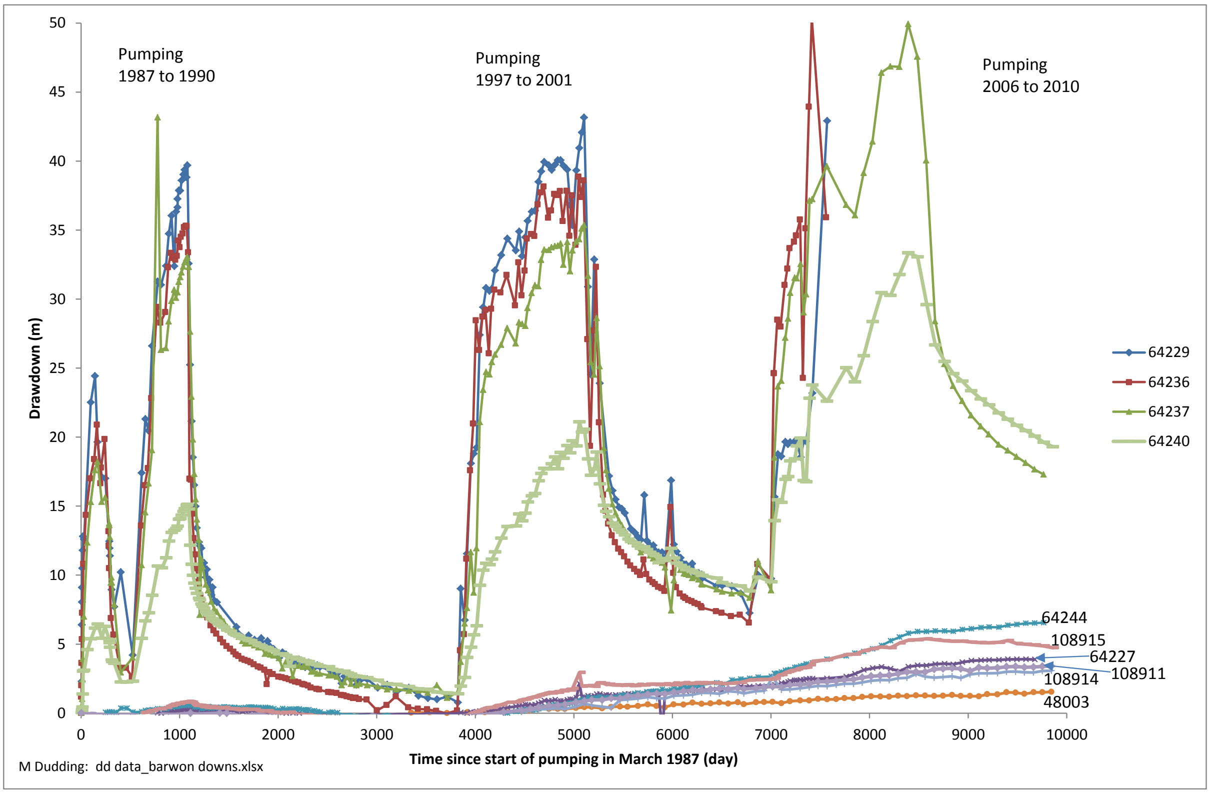


Figure 2: Drawdown in the Lower Tertiary Aquifer observation bores since start of bore field operation in 1986.



2.2 Homogeneous Aquifer

2.2.1 Confined

In a heterogeneous aquifer drawdown should propagate uniformly in all directions, and decrease in a uniform manner at increasing distance from the site of pumping. The Theis model is used to predict drawdown for this type of conceptual model.

Drawdown in the ten observation bores are clearly divided into two distinct groups, one with a rapid response to the three periods of pumping at the bore field since 1986, and the other with a very subdued response to pumping (Figure 2). Drawdown in the subdued bores is 15 to 30 times lower than expected if the aquifer had uniform hydraulic properties (ie a heterogeneousaquifer) similar to those for the rapid response bores (Table 1, Figure 3, Figure 4, and Figure 5).

A lower than expected drawdown, in a heterogeneous aquifer, is typically indicative of a higher than expect transmissivity. Using an heterogeneous model a high transmissivity of 2,700 m^2/day (Figure 6) is obtained from the early time drawdown in the subdued bores, but analysis of the late time indicates a lower transmissivity of 126 m^2/day (Figure 7). In both cases the analysis results in a storage co-efficient that is too high for a confined aquifer that is less than 500 m thick (0.06 and 0.04 for the early and late times respectively, Figure 6 and Figure 7). If the storage co-efficient is fixed to a value of 0.0004 (similar to that for the rapid response bores) a reasonable fit is obtained to the early time drawdown but this requires the transmissivity be unrealistically high at 20,000 m^2/day (Figure 8).

The Theis model has a superior fit to the rapid response bores but the fit to the recovery periods become poorer after each period of pumping. This tends to indicate non-uniform aquifer conditions typical of a boundary or boundaries, or variable storage properties (ie presence of confined and unconfined conditions). An improved fit to the later recovery periods can be obtained by reducing the transmissivity and increasing the storage co-efficient which tends to indicate varying aquifer transmissivity and storage co-efficient (Figure 9).

The difficulty in obtaining reasonable results using the Theis confined aquifer model for the subdued bores strongly indicates the aquifer is non-uniform (ie heterogeneous), and potentially of limited areal extent (ie bounded). Semi-confined (ie leaky) aquifer conditions and/or unconfined conditions (eg the Barongarook High) may also be present, as indicated by the high storage co-efficient for the subdued bores.

It is possible that other influences, such as declining rainfall or other pumping sources, may be the cause of the poor fit of the drawdown curves to an heterogeneous model (but this is considered unlikely, as the effect of declining rainfall is likely to be in the order of 1-2 metres, whereas the difference between predicted and actual response for the subdued bores (in the heterogeneous model) is many times greater than this). Although the effects of drought are not being directly examined in this report, the results may provide an insight into the degree to which drought may have impacted on groundwater levels (refer to Section 4).

The following sections examine the potential for the aquifer to be semi-confined, bounded, or heterogeneous.

Table 1: Observation bore response to pumping, drawdown, and distance from bore field

Bore ID	Response to pumping	Distance from bore field (km)[1]	Drawdown at end of second pumping period (1997 to 2001)[2]	Expected drawdown at subdued site using T and S from rapid response bore 64237 (m)
64229	Rapid	1.7	43.0	N/A
64240	Rapid	4.6	20.4	N/A
64236	Rapid	4.9	38.6	N/A
64237	Rapid	6.4	35.4	N/A
64244	Subdued	7.5	1.0	33
108915	Subdued	8.0	2.0	31
64227	Subdued	9.1	1.2	29
48003	Subdued	10.9	0.4	26
108914	Subdued	12.9	0.7	23
108911	Subdued	13.7	0.9	22

1. Distance is from production bore GW4
2. The second pumping period was selected due to some bores no longer being monitored during the 3rd pumping period (2006 to 2010)

Figure 3: Relationship between drawdown at end of 1997-2001 pumping period and distance from bore field (GW4)

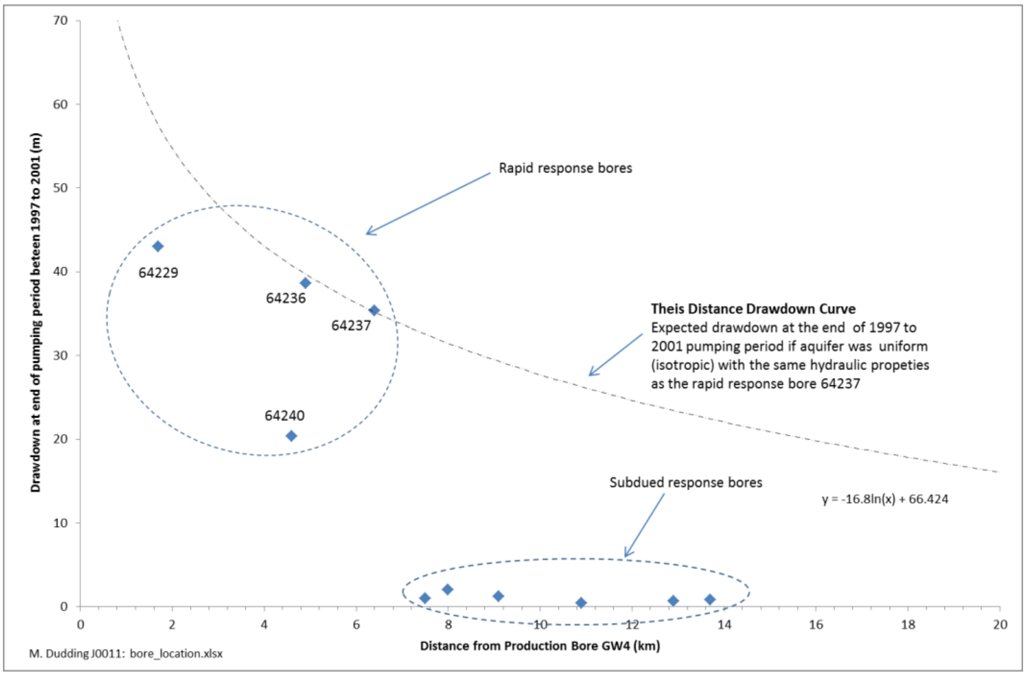


Figure 4: Drawdown expected for bore 108915 (blue curve) if the aquifer had uniform hydraulic properties similar to bore 64237

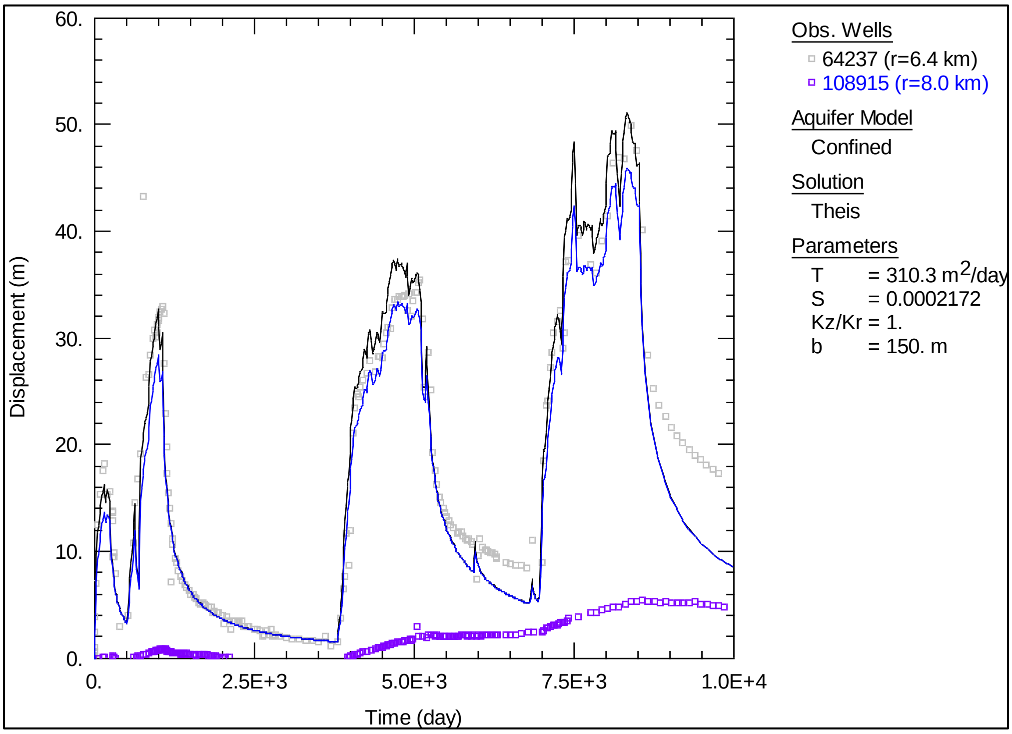


Figure 5: Drawdown expected for bore 108911 (blue curve) if the aquifer had uniform hydraulic properties similar to bore 64237

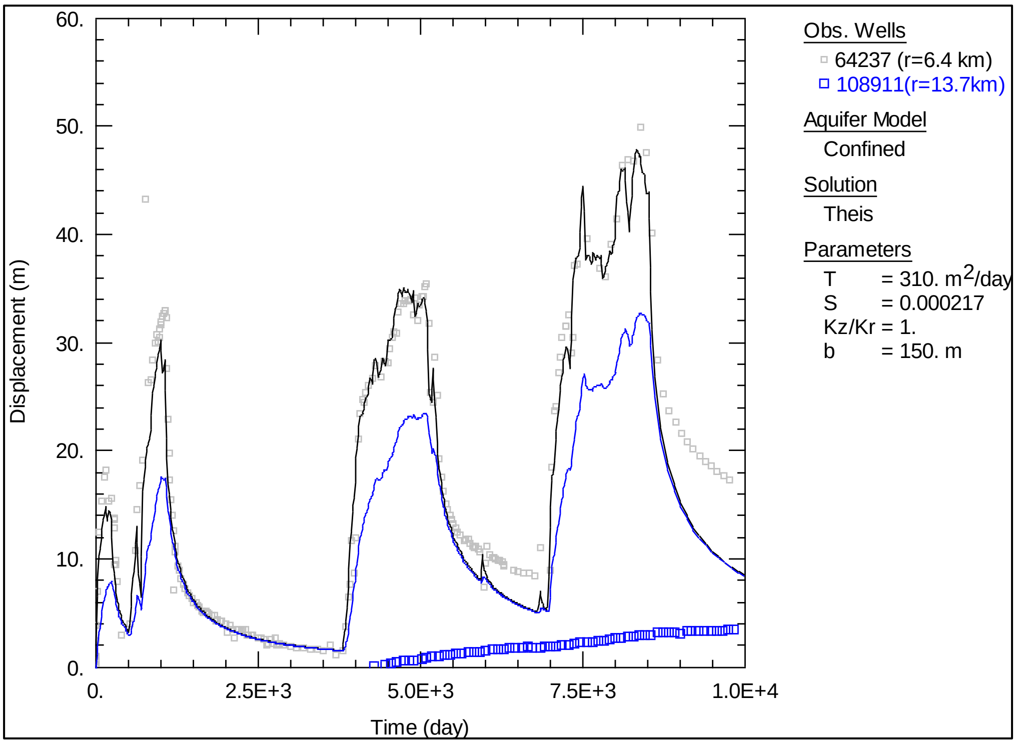


Figure 6: Analysis of subdued bores fitted to the early time data

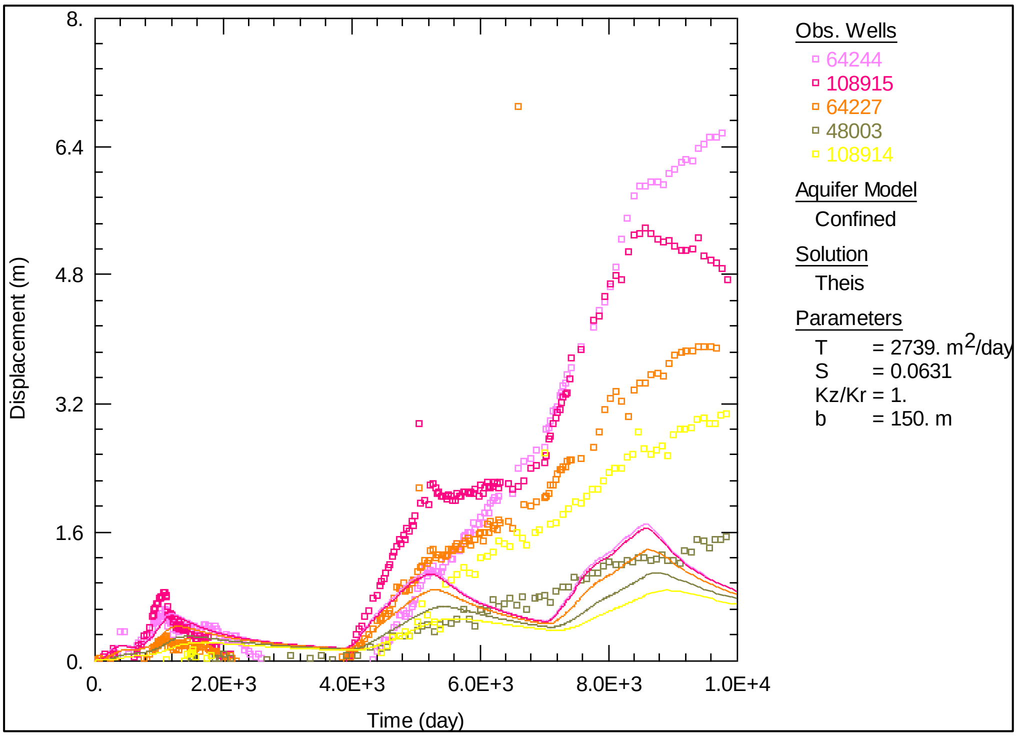


Figure 7: Analysis of subdued bores fitted to the late time data

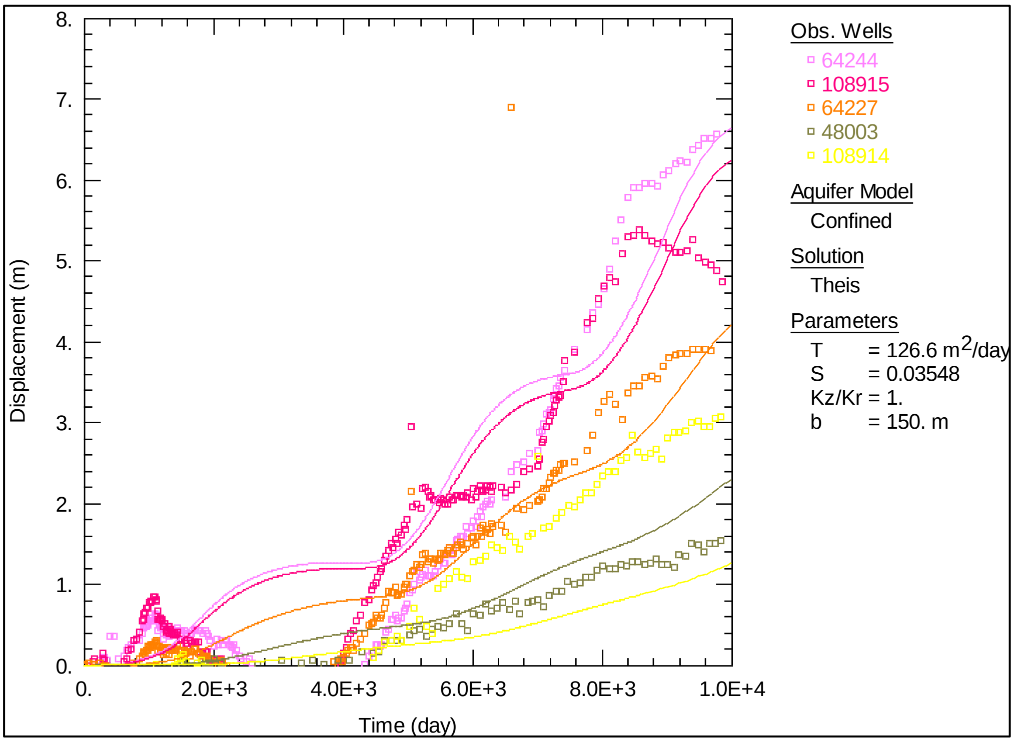


Figure 8: Analysis of subdued bores fitted to the early time data with S fixed at 0.0004

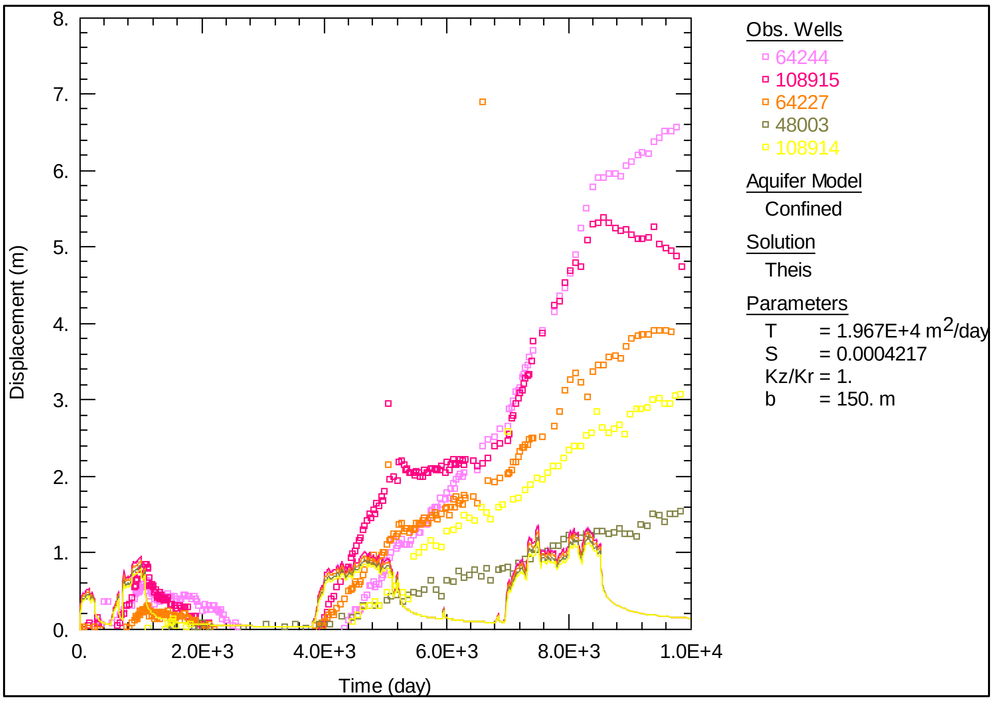
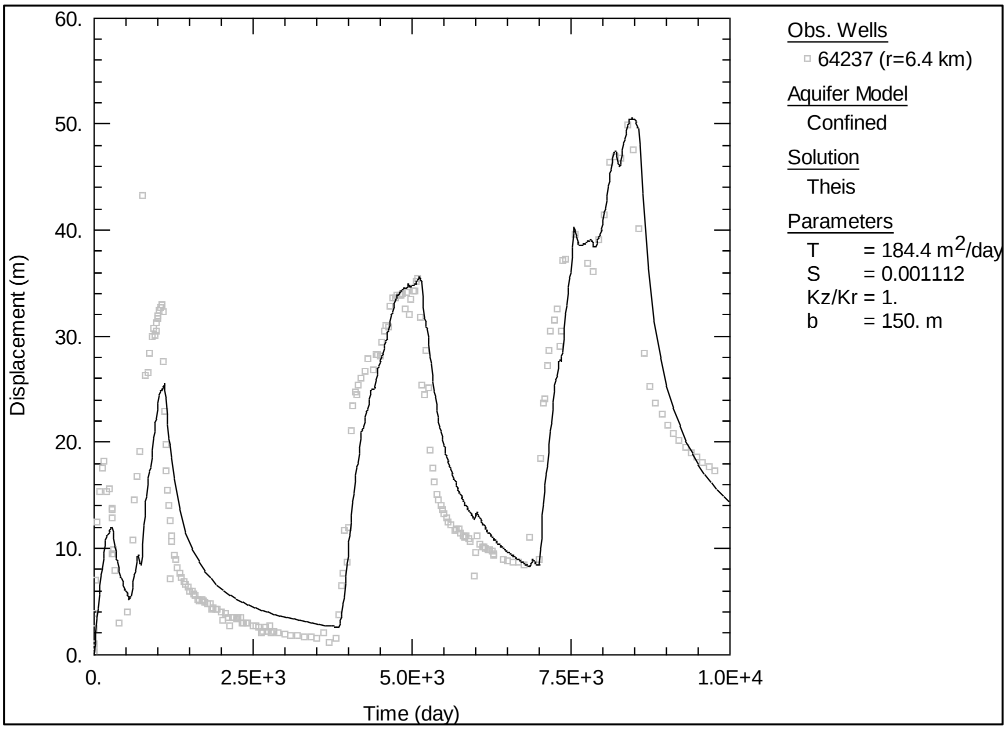


Figure 9: Lower Transmissivity and higher Storage Co-efficient obtained by fitting curve to the 2nd and 3rd recovery (ie non-pumping) periods (compare with Figure 5)



2.2.2 Semi-Confined

Leakage from an aquitard into a semi-confined heterogeneous aquifer can be represented by two general concepts:

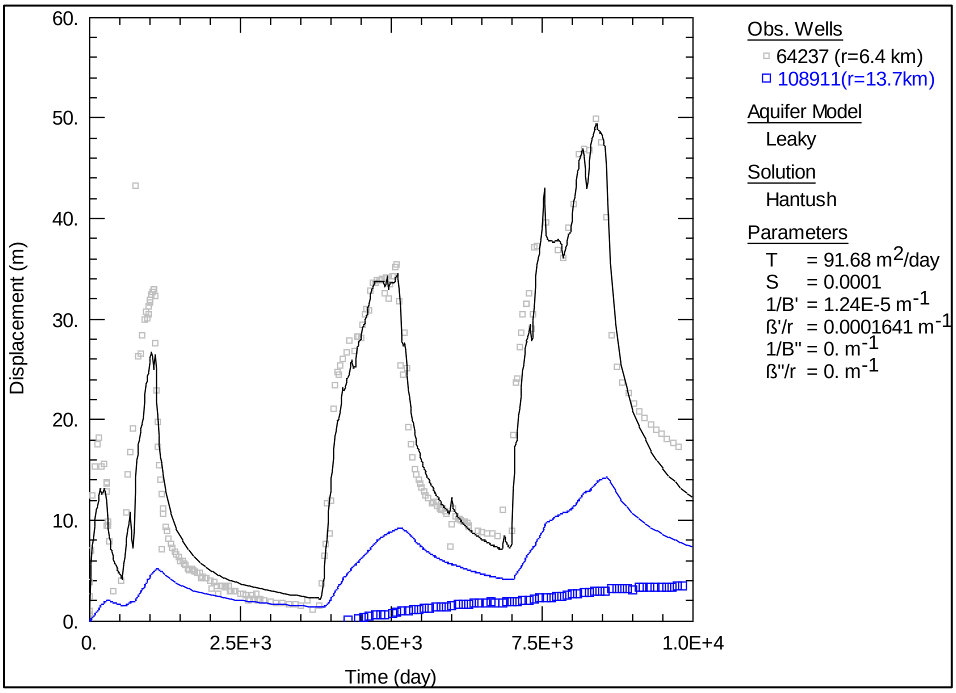
1. where leakage is derived by an aquifer overlying the aquitard and there is no release of groundwater stored in the aquitard (Hantush – Jacob, 1955)
2. where leakage is derived from groundwater stored within the overlying aquitard into the aquifer (Hantush, 1960)

The Hantush 1960 model has been chosen for this assessment due to the large volume of groundwater stored in the aquitard (due a thickness of up to 500 m) and the absence of an overlying aquifer.

The Hantush (1960) model provides a significantly improved match to the rapid and subdued response bores (Figure 10) compared to the confined models applied in the previous section. This may be due to the lower transmissivity in response to the model allowing leakage of groundwater into the aquifer. The improved, but still relatively poor, match to the subdued bores is due to both the lower transmissivity but also leakage from the aquitard, even though the resultant aquitard vertical hydraulic conductivity (Kv) is relatively low at 4 x 10^{-6} m/day.

The improved match to the subdued bore (although the match is still very poor) indicates that semi-confined conditions may be a contributing factor to the low drawdown in the subdued bores.

Figure 10: Semi-confined model with aquitard storage (Hantush, 1960)



2.3 Bounded Aquifer

2.3.1 Confined

A confined aquifer with barrier boundaries cause drawdown to be greater than a non-bounded aquifer during periods of pumping, and a slower rate of recovery during non-pumping periods.

For the rapid response bores very little improvement in the match to the recovery data during the 2nd and 3rd non-pumping periods is obtained by incorporating a single straight line boundary within the aquifer - representing the aquifer contact with the bedrock (located 5 km to the south of the bore field, Figure 11). Similarly there is little or no improvement to the match for the subdued bores (Figure 11). Unsurprisingly there is a significant increase in transmissivity to account for the presence of the boundary.

Including a second aquifer boundary representing the Colac Fault and aquifer/bedrock contact near Colac further degrades the match to the rapid and subdued response bores and requires a very high aquifer transmissivity (Figure 12). However, the two boundary model does display slower recovery rates after each period of pumping indicating that the aquifer is non-uniform, most probably a variability of transmissivity rather than solely an abrupt termination of the aquifer (as represented by a model boundary).

Although these barrier boundaries actually occur, the poor match to the observed data, particularly the subdued bores, suggests that the aquifer properties between the boundaries have a greater influence on drawdown than the boundaries themselves. However, this model does indicate that the barrier boundaries have some influence on the drawdown, most likely the poor water level recovery after each successive pumping period in the rapid response bores (ie the infinite aquifer extent assumption does not apply to the aquifer). This is consistent with the current conceptual model which comprises regions where the aquifer is confined (eg at the bore field) and unconfined (eg the Barongarook High). However, variability of transmissivity is less well understood although earlier numerical models (Witebsky *et al*, 1995) have indicated that there is significant variability of the aquifer transmissivity.

Figure 11: Confined model (Theis) with single aquifer boundary 5 km from the bore field

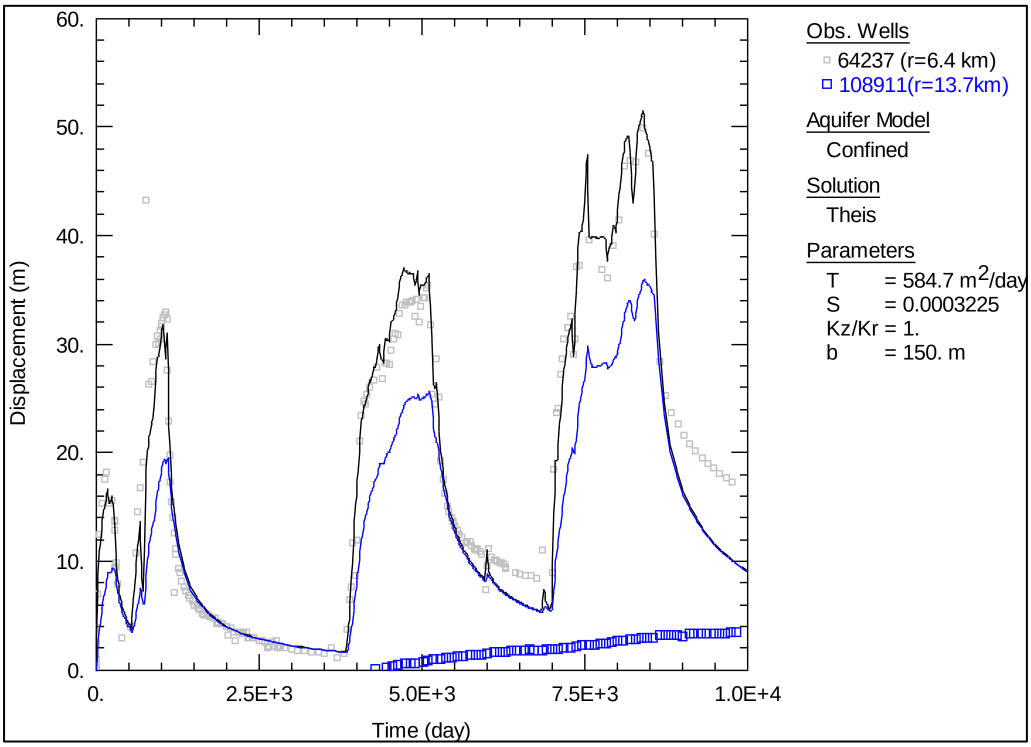
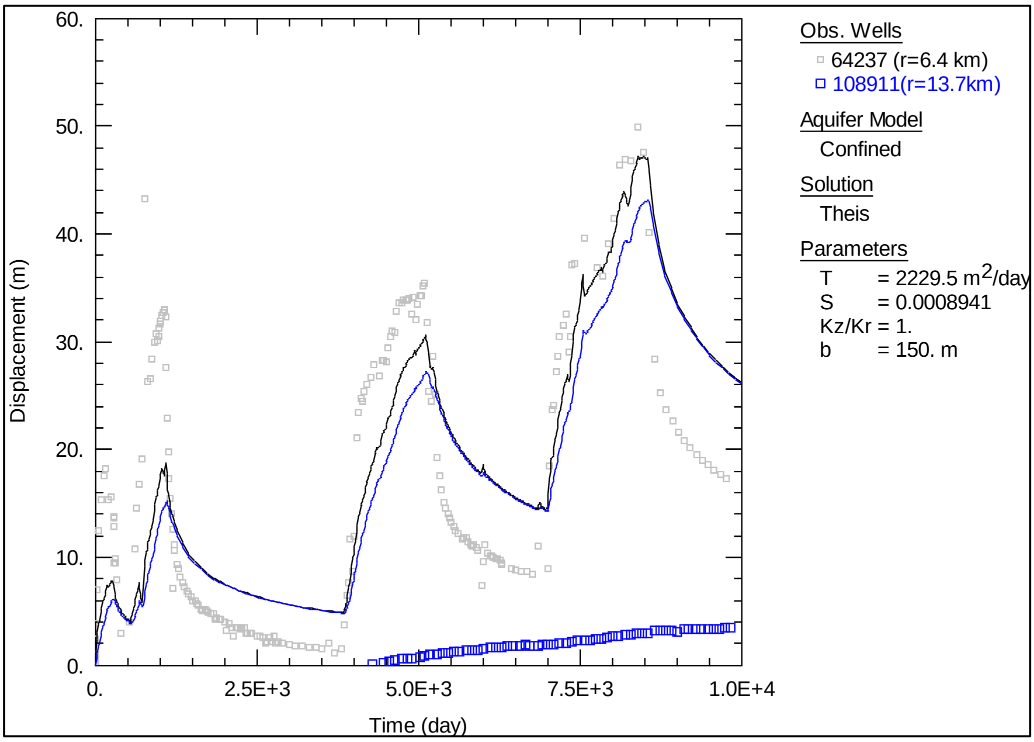


Figure 12: Confined model (Theis) with two parallel aquifer boundaries, at 5 km and 10 km from the bore field



2.3.2 Semi-Confined

A significant improvement in the match to the rapid response bores to the one and two boundary models indicates that leakage in combination with aquifer boundaries are significant factors influencing drawdown (Figure 13 and Figure 14).

However, the poor match to the subdued bores indicates that semi-confined conditions are not the primary factor causing the small amount of drawdown in these bores.

The inclusion of aquifer boundaries has required a significant increase in aquifer transmissivity (unsurprisingly), and significantly reduced the aquitard vertical hydraulic conductivity (Kv) from 10^{-6} m/day for the unbounded model to 10^{-13} m/day for the bounded model. Although 10^{-13} m/day is an extremely low value it demonstrates that such low values of aquitard Kv can have an impact on drawdown (ie compare drawdown in 64327 for the confined bounded case in Figure 12 and the semi-confined bounded case in Figure 14). In the two boundary case leakage from the aquitard allows for a greater rate of water level recovery during the non-pumping periods even though the transmissivity and storage co-efficient (ie compare confined model in Figure 12 with semi-confined model in Figure 16).

NOTE: due to the poor match to the subdued bores the model used is unlikely to be representative of the conceptual model and, as such, the reported aquitard Kv is unlikely to be representative.

Figure 13: Semi-confined model with aquitard storage and single aquifer boundary 5 km from the bore field for 64237 and 108911

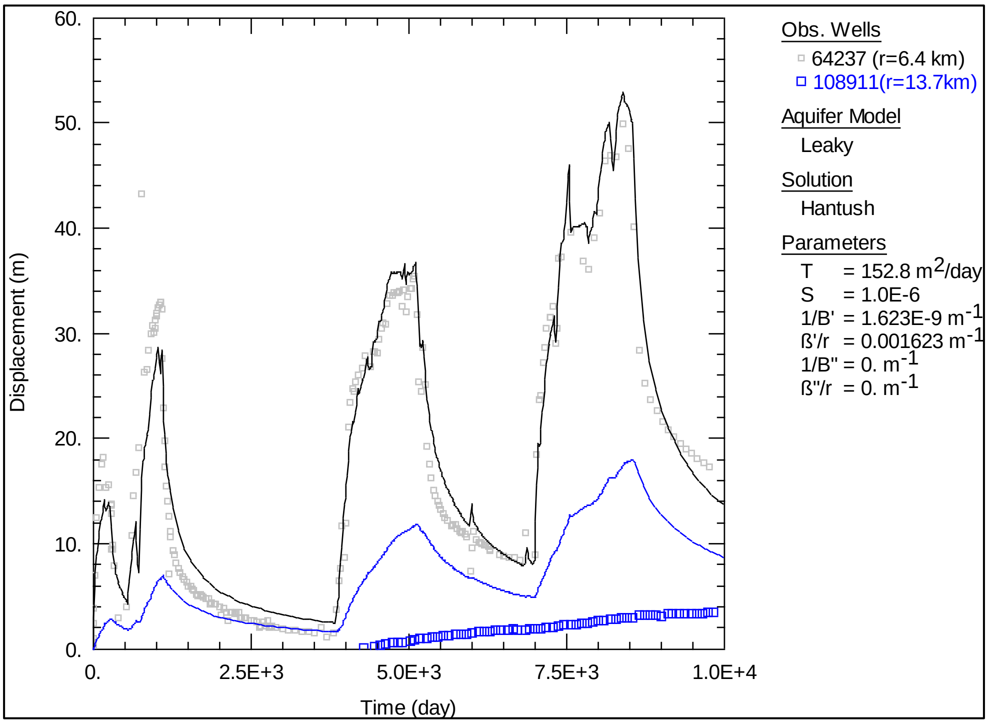


Figure 14: Semi-confined model with aquitard storage and two parallel aquifer boundaries, at 5 km and 10 km from the bore field for 64237 and 108911

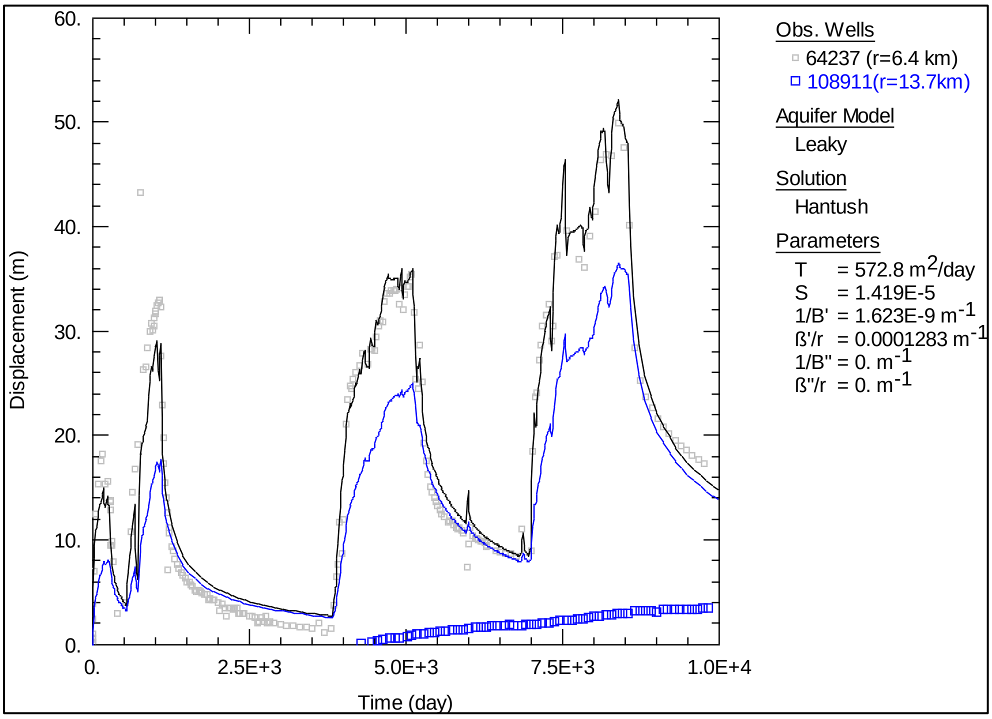


Figure 15: Semi-confined model with aquitard storage and single aquifer boundary 5 km from the bore field for 64237 and 108915

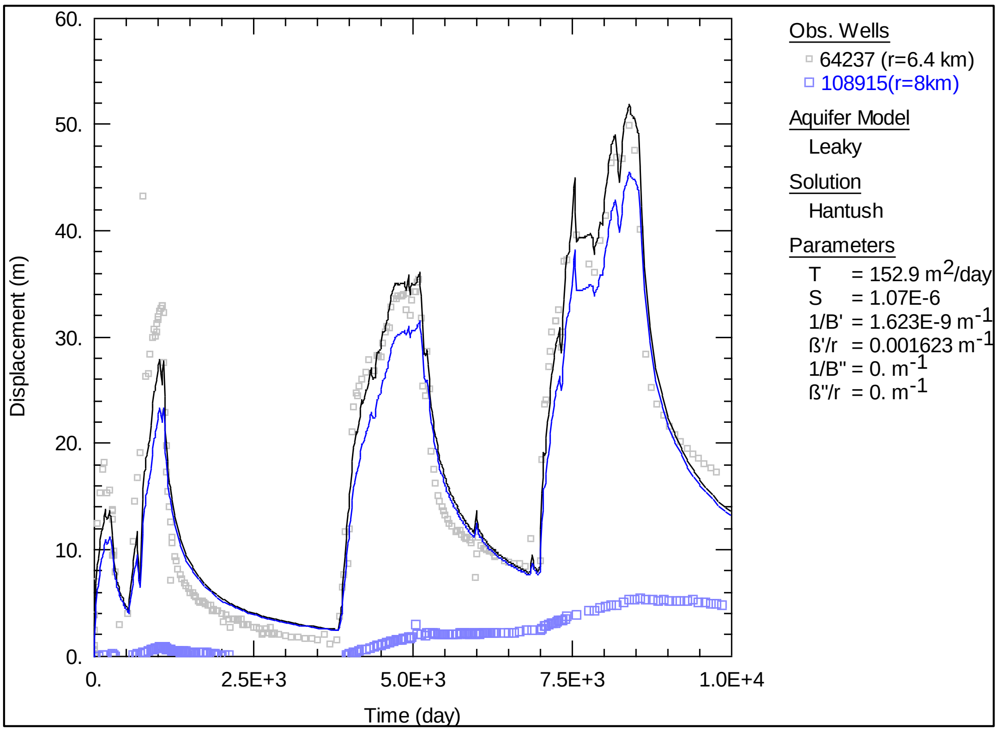
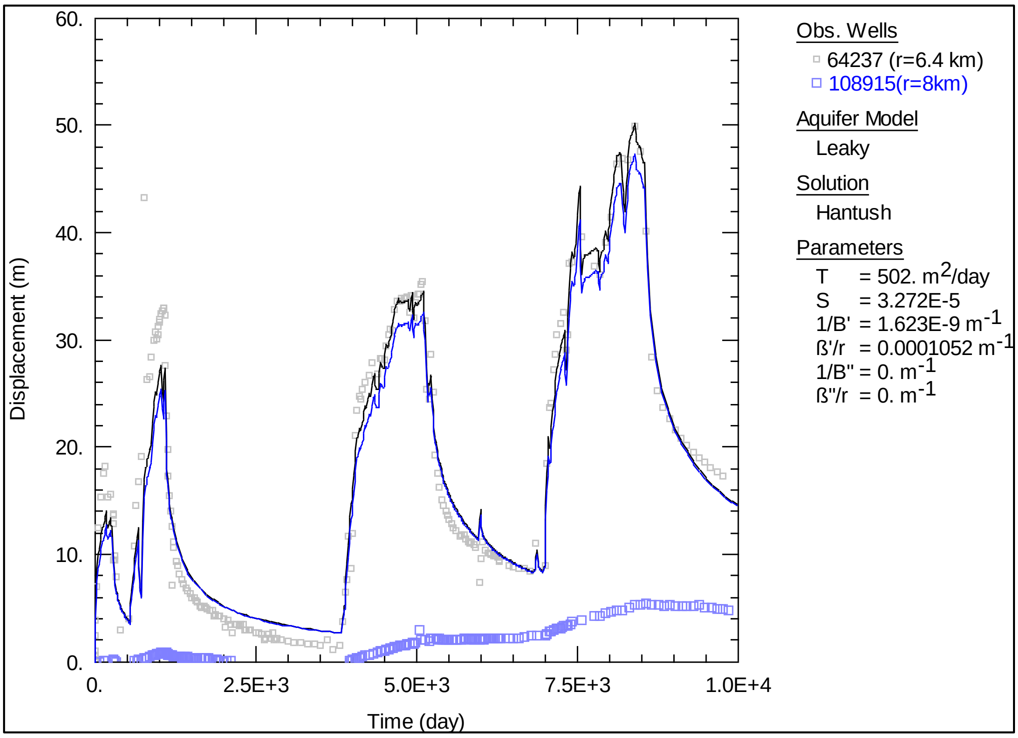


Figure 16: Semi-confined model with aquitard storage and two parallel aquifer boundaries, at 5 km and 10 km from the bore field for 64237 and 108915



2.4 Heterogeneous Aquifer

The superior match to the rapid response bores to the bounded models, for confined and semi-confined aquifers indicates that the aquifer is of limited areal extent and/or there is a large reduction in transmissivity at the location of the boundaries. However, the poor match to the subdued bores indicates that the variability of aquifer transmissivity may also occur within the aquifer (ie there might be multiple zones of significantly different transmissivity rather than just a truncation of the aquifer at natural limits of aquifer extent).

The relatively high storage co-efficient required to produce a lower drawdown more representative of the subdued bores suggests that there is a change in aquifer storage co-efficient within the aquifer. This could be due to the unconfined conditions present on the Barongarook High and possibly the unconfined area on the south side eastern side of the Bambra Fault. However, a zone of high aquitard leakage could also account for the limited drawdown in the subdued bores.

The superior match to the semi-confined bounded model compared to the confined bounded model indicates that semi-confined (ie leaky) aquifer conditions are present.

The analysis using the confined and leaky and bounded aquifer models indicates that the aquifer in the vicinity of the south-west model area is complex, and likely to comprise zones of different transmissivity and storage co-efficient (ie is heterogeneous), is likely to be bounded and semi-confined.

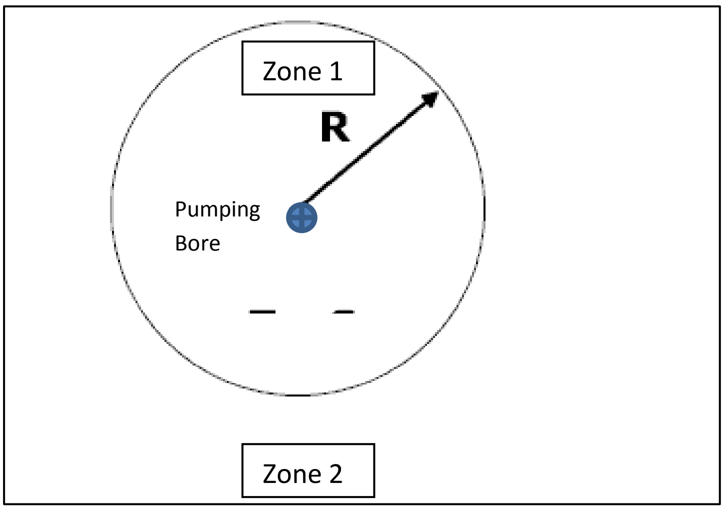
To examine the potential for anisotropy in the south-west model boundary the drawdown data was analysed using the Butler (1988) non-uniform aquifer model. This model allows prediction of drawdown in an heterogeneous confined aquifer comprising two concentric zones (Figure 17):

Zone 1. An inner zone with a defined radius centred on the pumping bore, and

Zone 2. An outer zone with an unlimited radial extent that fully encloses the inner zone.

The Butler model allows Zones 1 and 2 to have different values of transmissivity and storage co-efficient, and the radius of Zone 1 (R) to vary.

Figure 17: Plan view of Butler Model. The parameter "R" represents the radius of Zone 1. Zone 2 has an infinite extent



Zone 2

Rapid Response Bores

A good match is obtained for three of the four rapid response bores with a two zone aquifer comprising a high transmissivity (1,467 m^2/day), low storage co-efficient (0.0001) inner zone surrounded by a much lower transmissivity (191 m^2/day), higher storage co-efficient (0.001) outer zone (Figure 18). Rapid response bore 64237 occurs within the lower transmissivity zone, with all other bores occurring within the high transmissivity zone. However, bore 64240 has less drawdown than that predicted by the model suggesting the aquifer zones are not circular and/or the change in transmissivity and storage co-efficient do not coincide. When modelled in pairs a similar result obtained (ie high T, low S for Zone 1 and lower T and higher S for Zone 2) but the average transmissivity for both zones being significantly lower, and the storage co-efficient for zone 2 being significantly larger (Figure 19, Figure 20, Figure 21), as follows:

- Zone 1: 326 m^2/day and 0.00006
- Zone 2: 38 m^2/day and 0.076
- R = 10.9 km

The low transmissivity and/or high storage co-efficient of the outer zone is acting in a similar manner to the bounded aquifer cases used in the confined and semi-confined aquifer models (refer to Figure 22 Figure 23 for comparison with Butler model in Figure 19). Note: the Butler model is unable to incorporate aquifer boundaries due to the non-uniform nature of the aquifer being modelled. If aquifer boundaries could be incorporated into the Butler model it is likely that the amount of drawdown predicted by the model would increase, requiring an increase to the inner zone transmissivity, and/or a decrease to the outer zone transmissivity or decrease or the storage co-efficient. The amount these values would need to change may be relatively small, but regardless of the amount of change this would not alter the conceptual model (ie confined high transmissivity inner zone and a semi-confined or unconfined, low transmissivity outer zone.

The current conceptual model for the Barwon Downs region comprises two distinct zones, a confined/semi-confined aquifer extending along an NE-SW axis with a radius of at least 20 km from the bore field, and three unconfined areas located approximately 6 km to the NW and SE of the bore field (ie the Barongarook High and the aquifer outcrop to the SE of the Bambra fault), and 20 km to the SW (ie outcropping aquifer near Gellibrand). The radius (R) of the inner modelled zone from the Butler analysis varies from 4 km to 20 km which may reflect the various distances between the bore field and the outcropping aquifer (in the current conceptual model).

It is worth noting that the “R” values are similar to the radial distance between the bore field and the outcropping area along the flow line (during pumping) between the bore field and the most distant bore (eg the “R” value for bores 64229/64240 is 4 km, and the vector length between GW4 and the Barongarook High through bore 64240 is 6 km. The “R” values for 64229/64237 and 64229/64236 are 20 km and 8 km respectively, and the vector lengths are 20 km and 6.5km). This tends to suggest that storage co-efficient is a greater influence on drawdown than transmissivity. However, the modelled zones are concentric whereas the aquifer is highly ellipsoid (ie elongated in NE-SW direction) so the “R” values may not be representative of the actual size of the inner zone.

Figure 18: Butler two zone model for all rapid response bores (note, the grey line for 64240 plots beneath orange line for 64236)

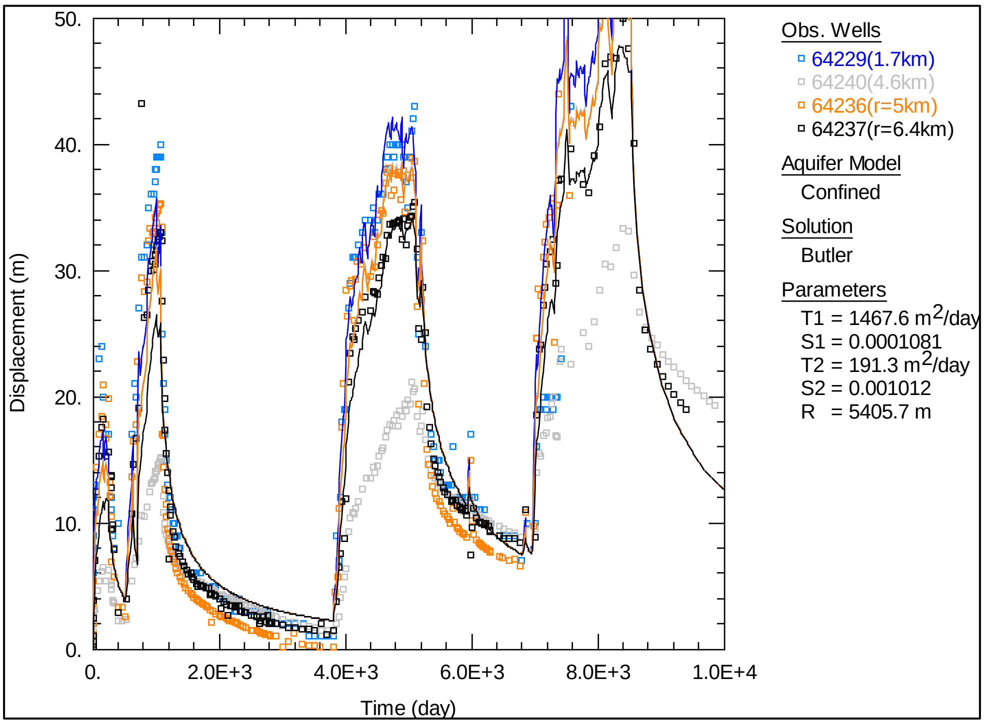


Figure 19: Butler two zone model for rapid response bores 64229 and 64240

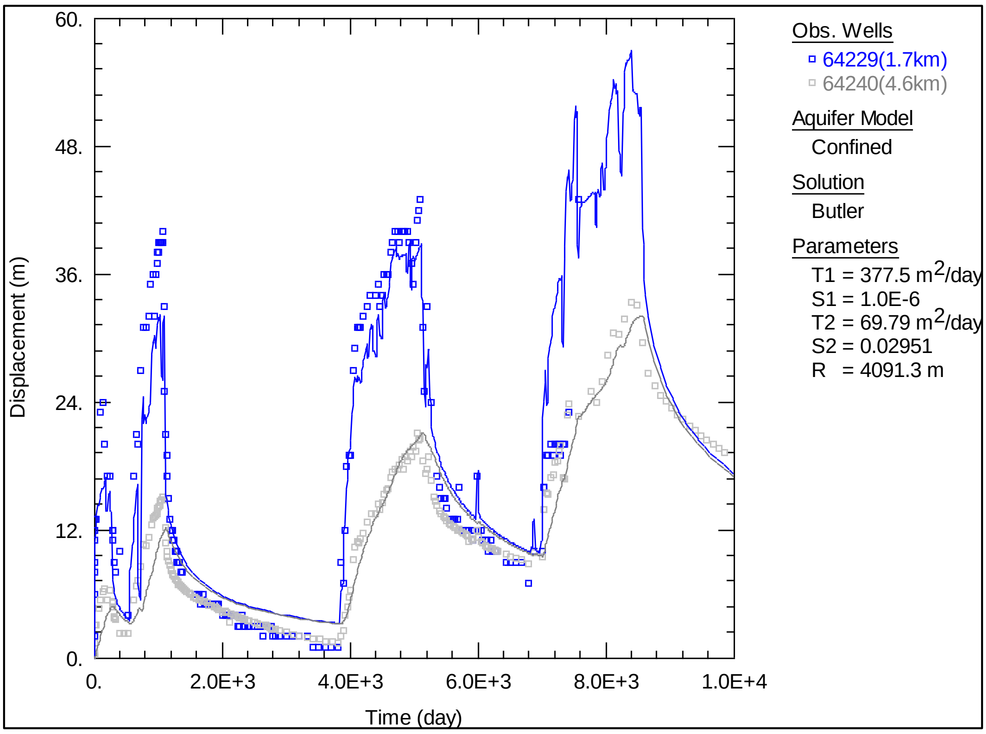


Figure 20: Butler two zone model for rapid response bores 64229 and 64237

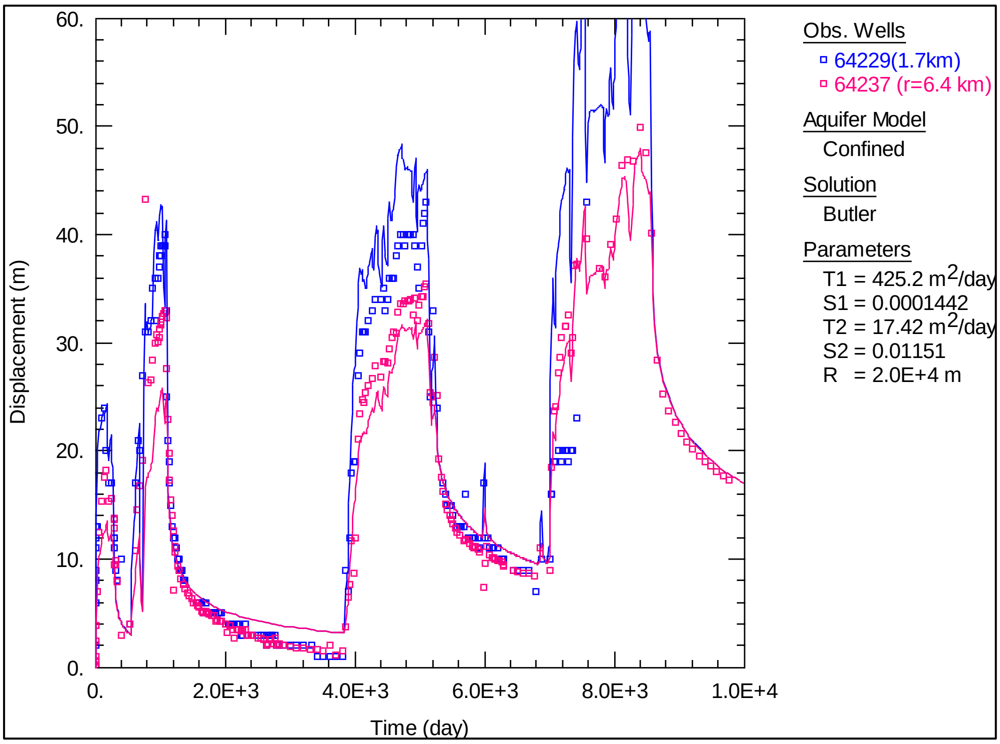


Figure 21: Butler two zone model for rapid response bores 64236 and 64237

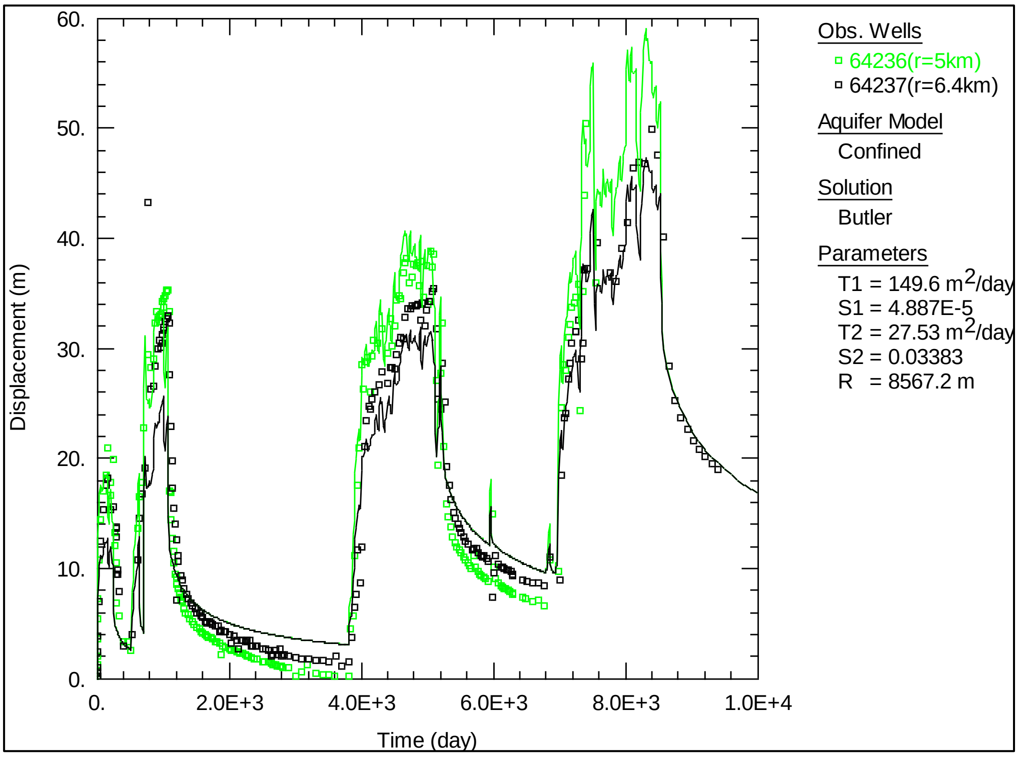


Figure 22: Confined (Theis) model with two boundaries for rapid response bores 64229 and 64240

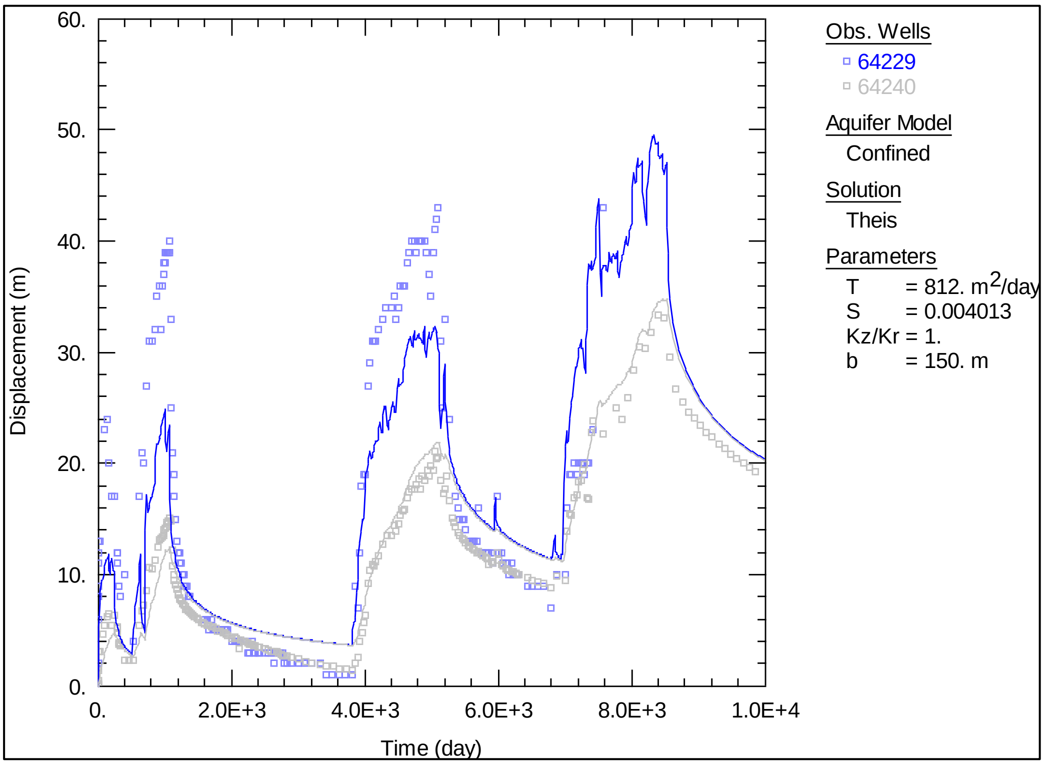
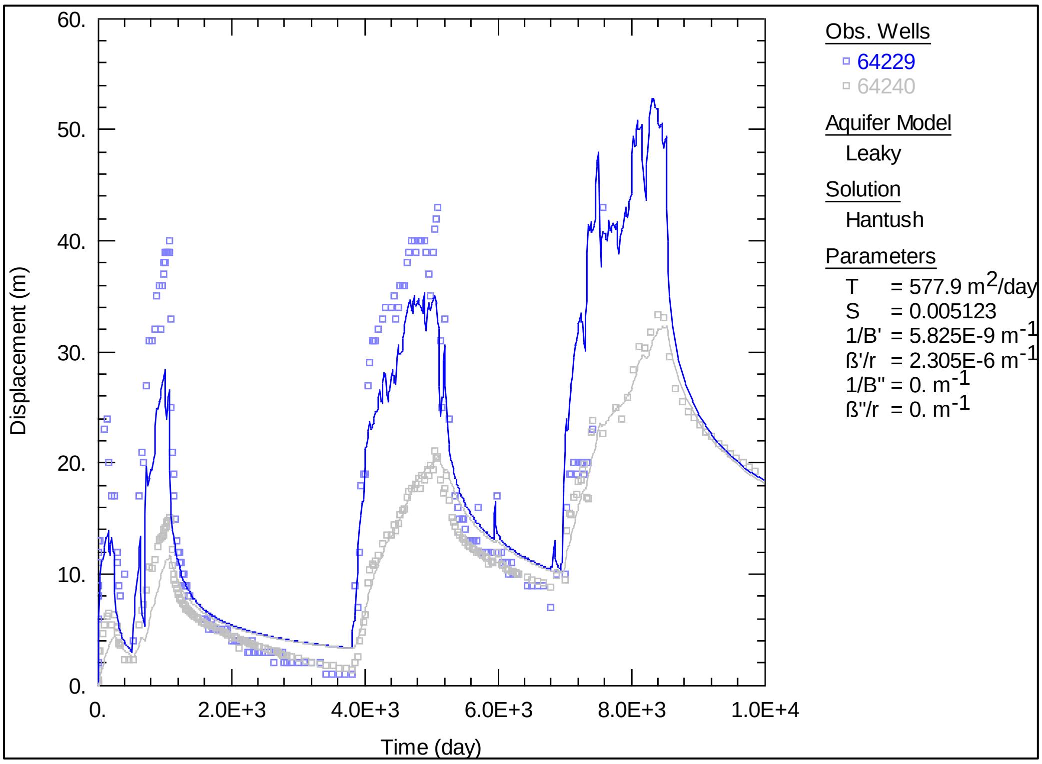


Figure 23: Semi-Confined (Hantush 1960) model with two boundaries for rapid response bores 64229 and 64240



Subdued Response Bores

Applying the subdued response bores to the best fit model for all the rapid response bores (Figure 18) produces a poor match, with the model predicting significantly more drawdown for the subdued bores (Figure 24). However, a very good match is obtained for all the subdued bores using the model for rapid response bores 64229 and 64240 (Figure 25 to Figure 29). Although the values of transmissivity and storage co-efficient for this model are different to the model for all the rapid response bores, this model also comprises a high transmissivity, low storage co-efficient inner zone surrounded by a lower transmissivity, high storage co-efficient outer zone (Figure 25 to Figure 29). This model provides the best fit to both rapid and subdued response bores which was not achieved using any of the previous models. The average transmissivity and storage co-efficient is given below and is very similar to the average from the individual rapid response bores models:

- Zone 1: 412 m^2/day and 0.000001
- Zone 2: 65 m^2/day and 0.035
- R = 4.1 km

However, a similarly good match can be made where rapid response bore 64236 or 64237 is used resulting in similar storage co-efficient for Zones 1 and 2, similar transmissivity for Zone 2, and a similar radius for Zone 1 (Table 2). The models using rapid response bores 64236 and 64237 have a much lower transmissivity for Zone 1 may be a consequence of these bores being close to the outer edge of Zone 1 or within Zone 2 and, as such, less sensitive to the presence of high transmissivity closer to the bore field due to the one way co-ordinate nature of transmissivity[1] (Jiao and Zheng (1997). Storage co-efficient has a two way co-ordinate nature so is less influenced by the position of the observation bore relative to the pumping bore (Jiao and Zheng (1997). As a result, the smaller radius of Zone 1 compared to the rapid response bores (10.9 km) is more likely to be reflective of the change in storage co-efficient rather than a change in transmissivity, unless they are co-incident (which is unlikely).

Due to the very good match with both rapid and subdued response bores it is likely that the two zone model is most representative of the all the models assessed. This suggests that the south-west boundary area or a zone between the bore field and the boundary is likely to comprise of an area of low transmissivity. The two zone model also indicates that a zone of high storage co-efficient is also a significant factor, possibly more significant than low transmissivity, influencing drawdown. The current conceptual model strongly indicates that any areas of high storage co-efficient are most likely to occur in the Barongarook High and/or on the south-east side of the Bambra Fault which are not in the immediate area of the model boundary. It is less certain, but possible, that the outcropping area of the aquifer along the Gellibrand River may also represent a zone of high storage co-efficient.

[1] The concepts of two-way and one-way coordinates describe the aquifer location most representative of the transmissivity and storage co-efficient obtained from an observation bore during a pumping test. A two-way coordinate is influenced by changes in conditions on either side of the observation bore relative to the pumping bore; a one-way coordinate is influenced by changes in conditions on only one side of the observation bore. Storage co-efficient has the characteristics of a two-way coordinate, but transmissivity has the characteristics of a one-way coordinate. This means storage co-efficient is representative of regions both upstream and downstream of the observation bore, but transmissivity is mainly representative of locations upstream of the observation bore (ie the region between the observation bore and the pumping bore). Note: during pumping, 'upstream' is the radial direction away from the pumping bore.

Table 2: Summary of average transmissivity, storage co-efficient, and Zone 1 radius for models using rapid and subdued response bores

Rapid response bore(s)	Distance from GW4 (km)	Subdued response bore(s)	Average Transmissivity Zone 1 (m^2/day)	Average Transmissivity Zone 2 (m^2/day)	Average Storage co-efficient Zone 1	Average Storage co-efficient Zone 2	Average radius of Zone 1 (km)
All	-	-	1,467	191	0.0001	0.001	5.4
64229	1.7	All	412	65	0.000001	0.035	4.1
64240	4.6						
64236	5.0	All	67	58	0.00026	0.11	6.9
64237	6.4	All	10	41	0.00014	0.09	6.7

Figure 24: Predicted drawdown for all subdued bores using Butler model matched to rapid response bores 64229, 64237, and 64236 (note: for clear presentation, only rapid response bore 64229 is plotted).

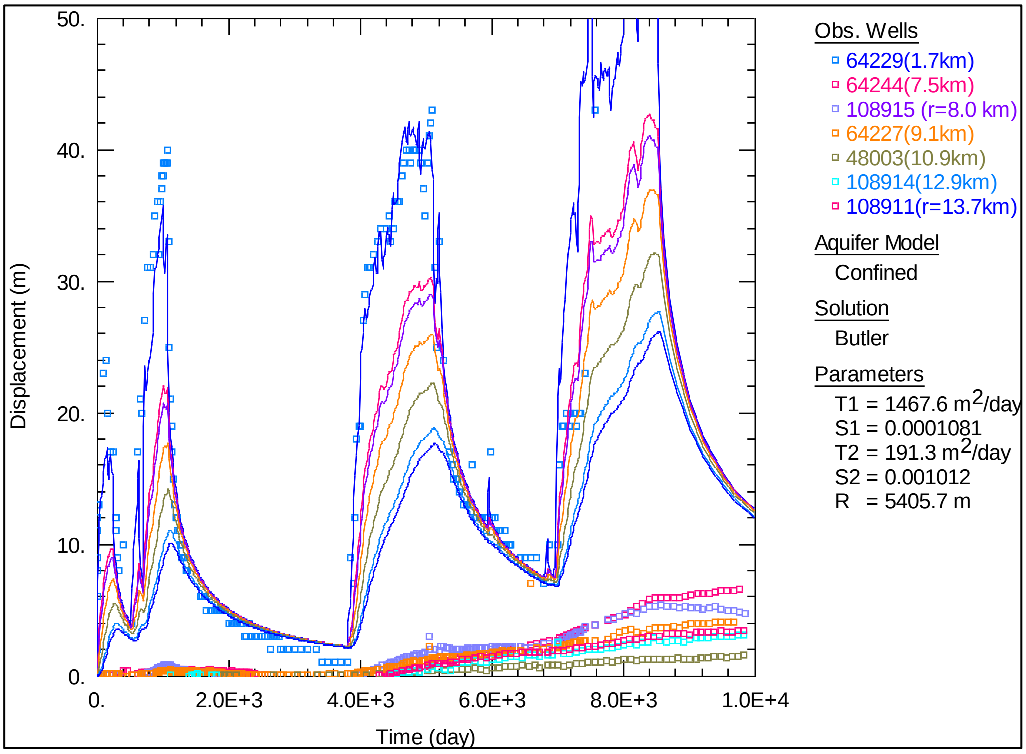


Figure 25: Butler two zone model for rapid response bores 64229 and 64240, and subdued response bore 48003

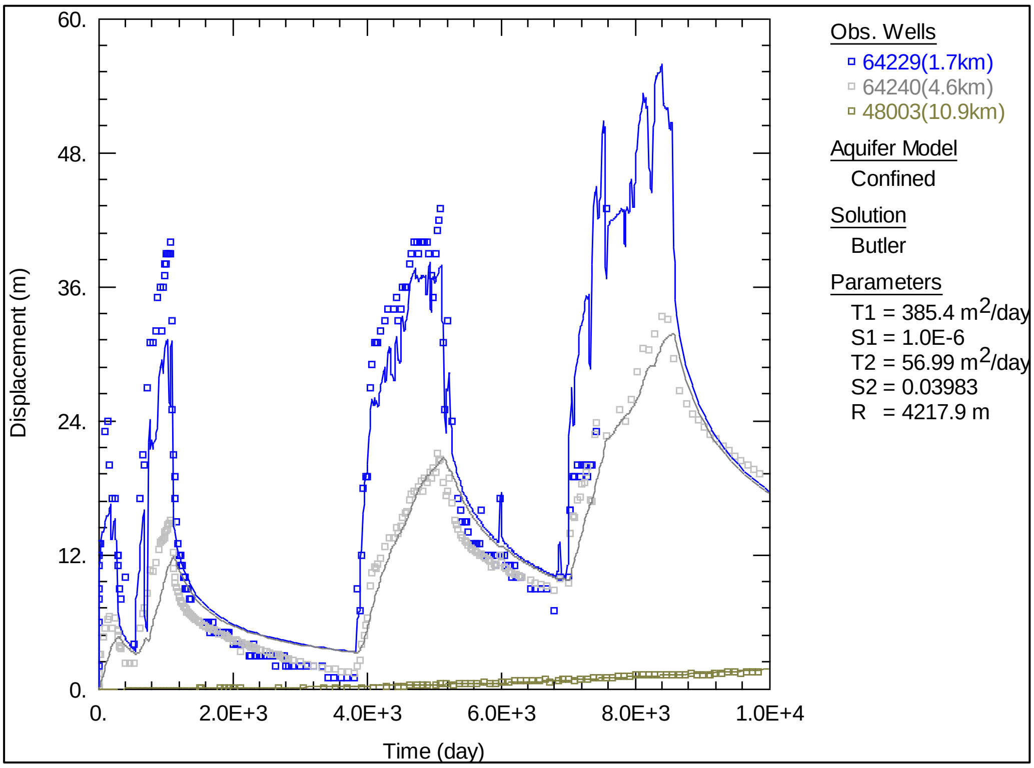


Figure 26: Butler two zone model for rapid response bore 64229 and 64240, and subdued response bore 64227

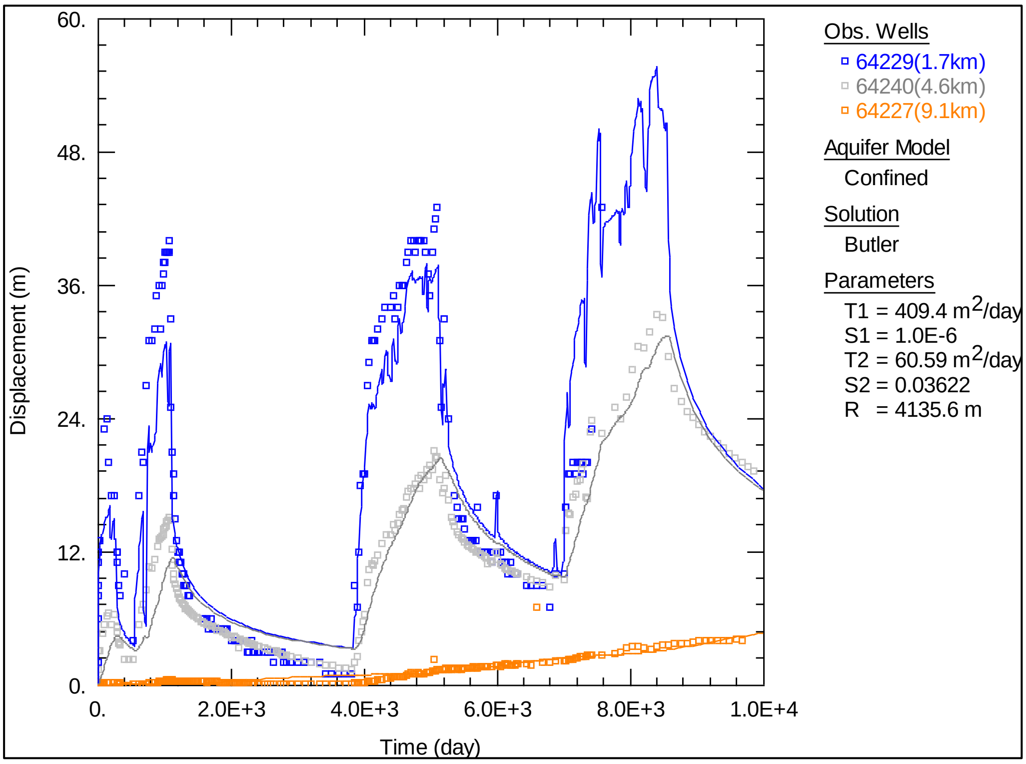


Figure 27: Butler two zone model for rapid response bore 64229 and 64240, and subdued response bore 108911

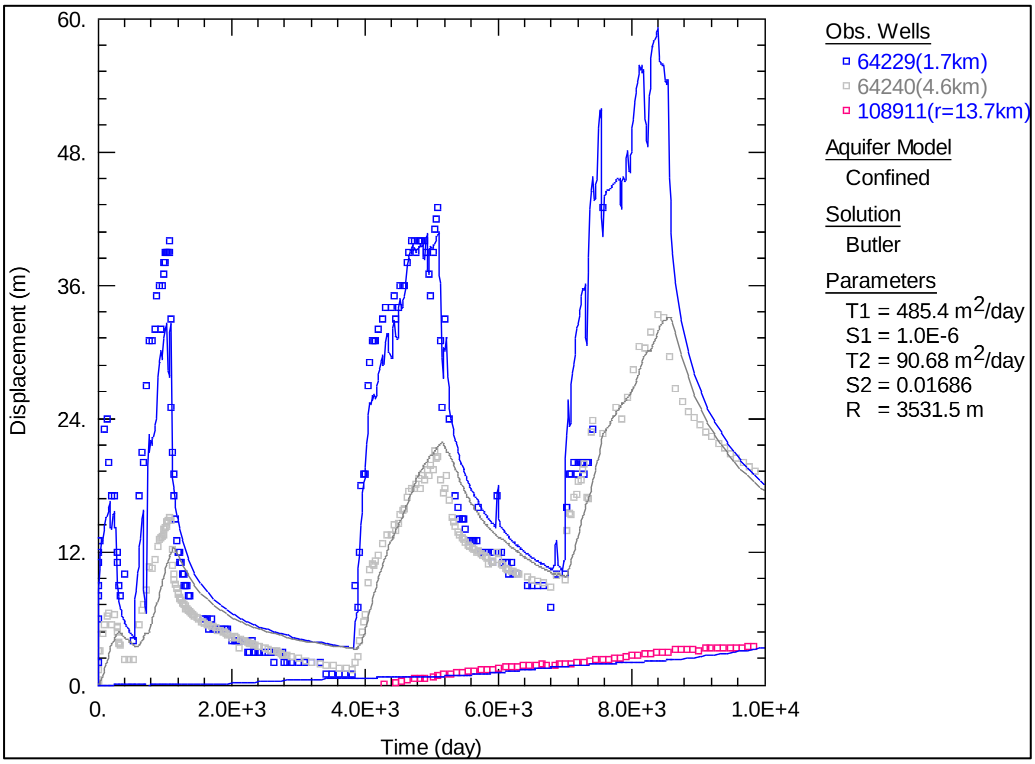


Figure 28: Butler two zone model for rapid response bore 64229 and 64240, and subdued response bore 108914

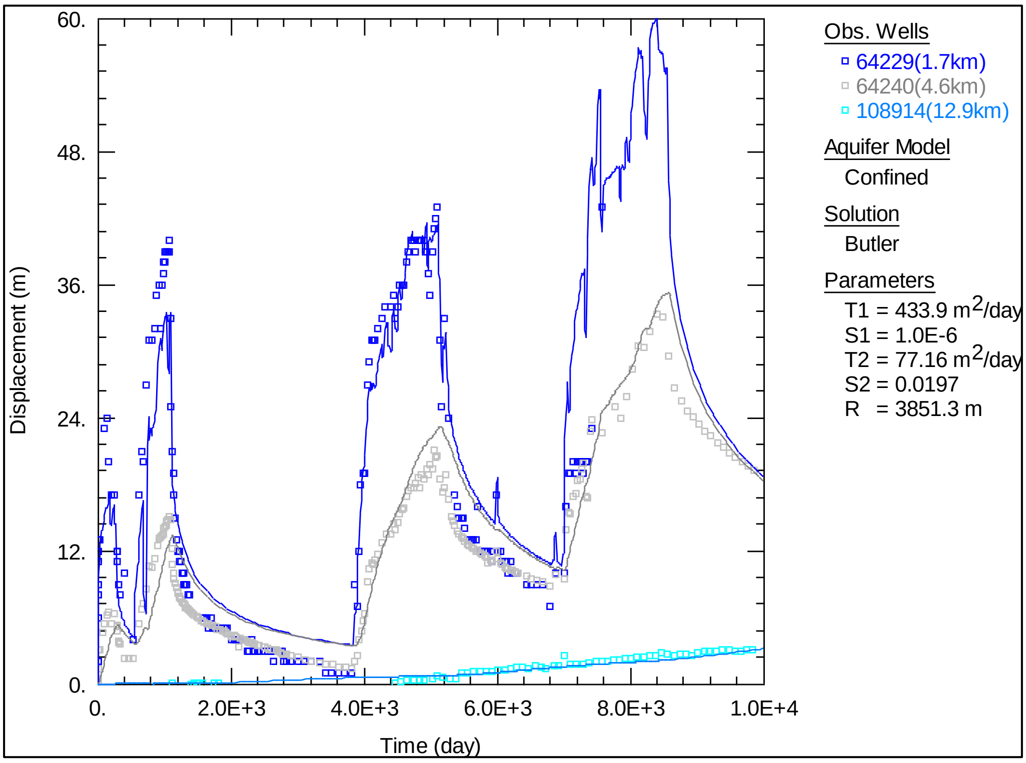


Figure 29: Butler two zone model for rapid response bore 64229 and 64240, and subdued response bore 108915

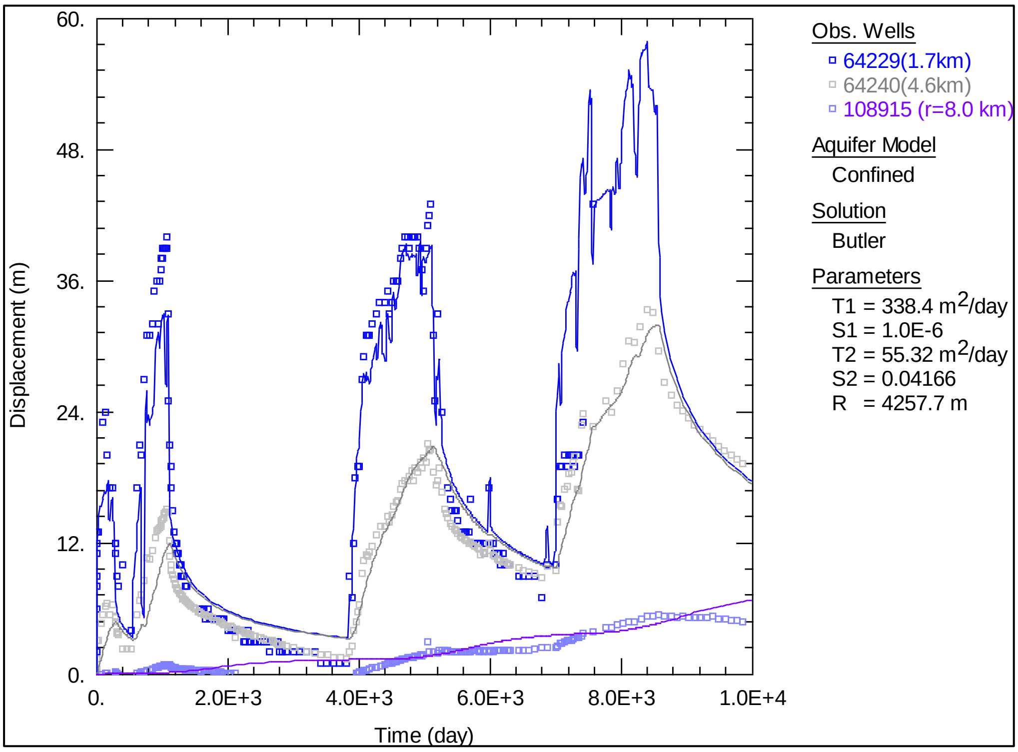


Figure 30: Butler two zone model for rapid response bore 64229 and 64240, and subdued response bore 64244

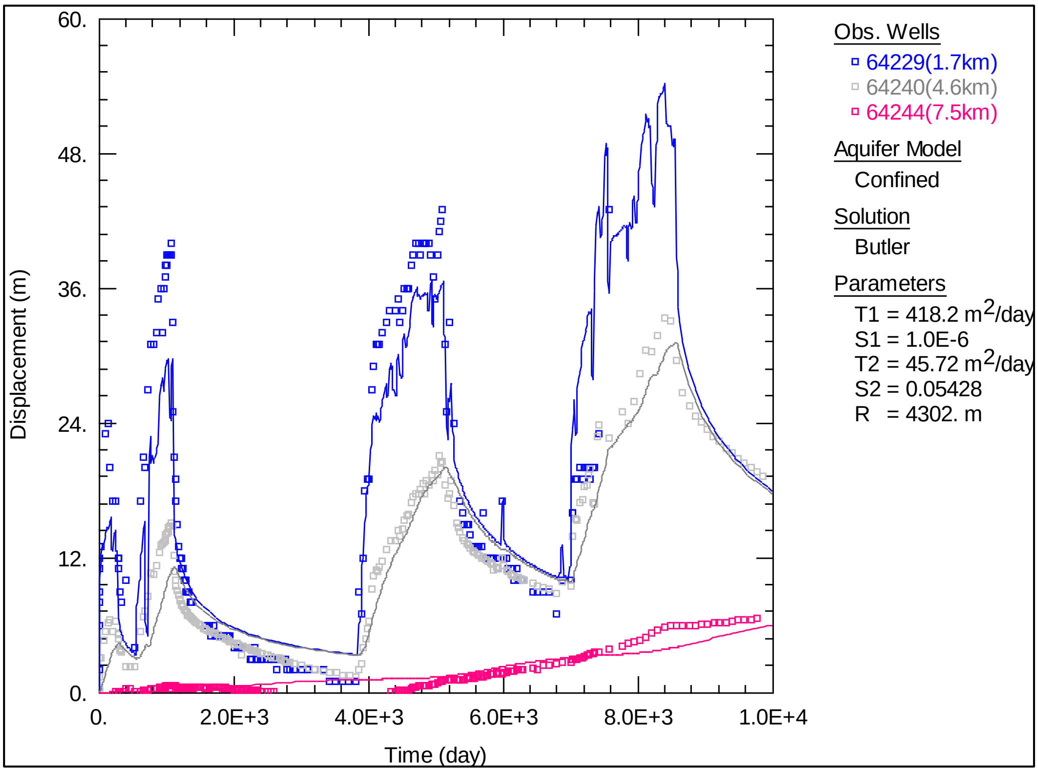


Figure 31: Butler two zone model for rapid response bore 64237 and subdued response bore 48003

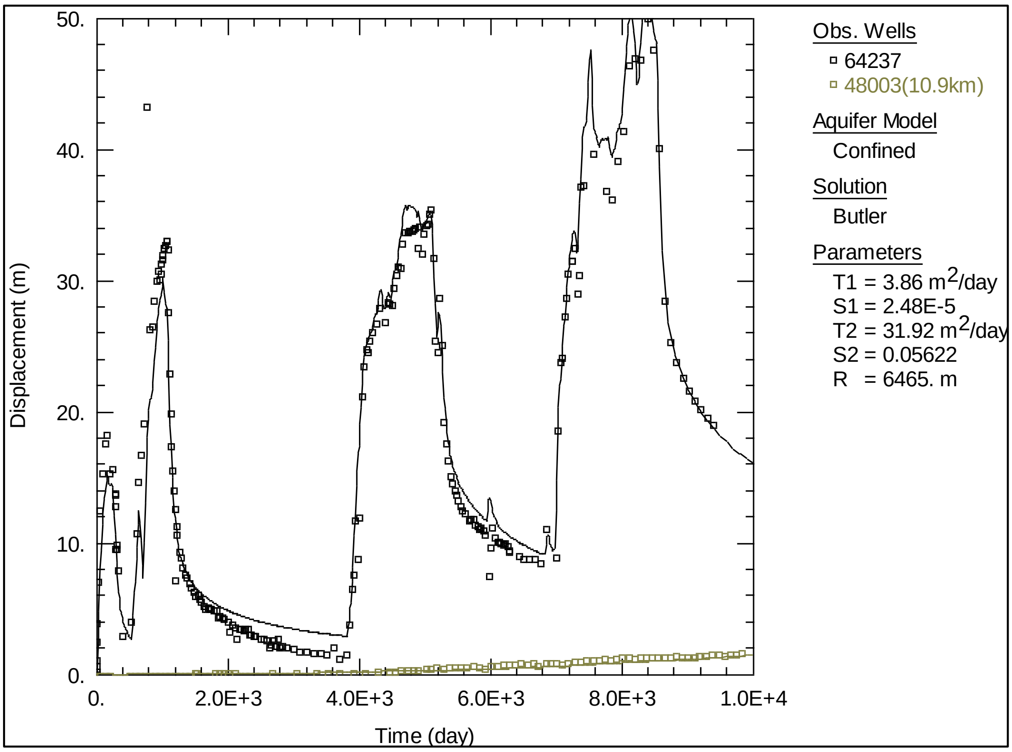


Figure 32: Butler two zone model for rapid response bore 64237 and subdued response bore 64227

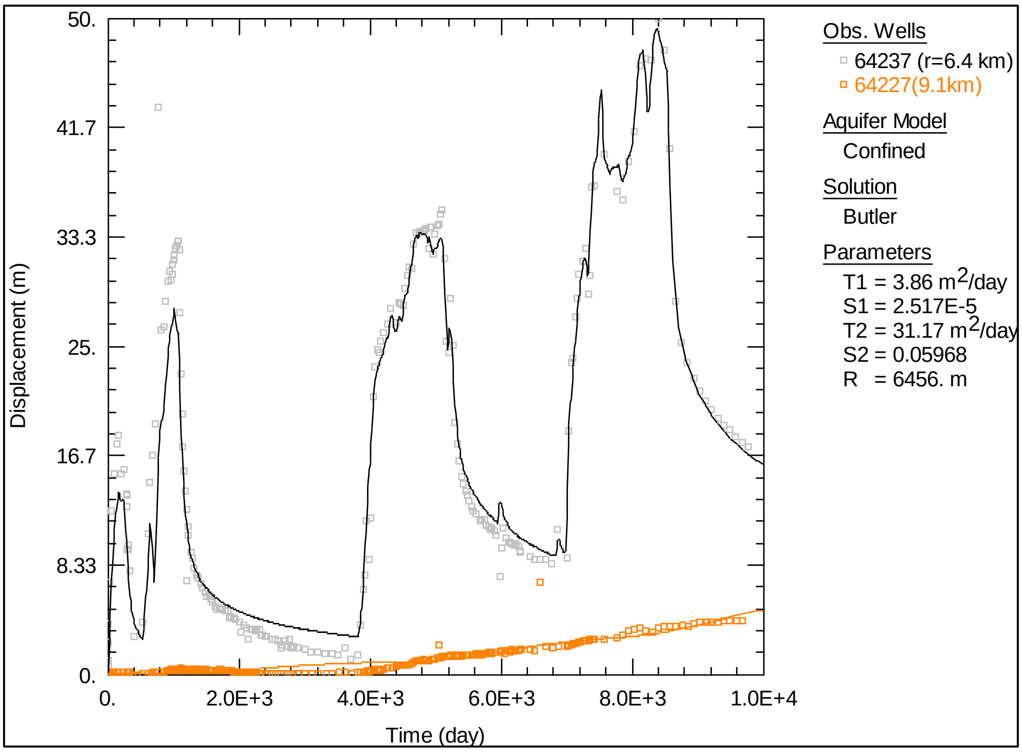


Figure 33: Butler two zone model for rapid response bore 64237 and subdued response bore 108911

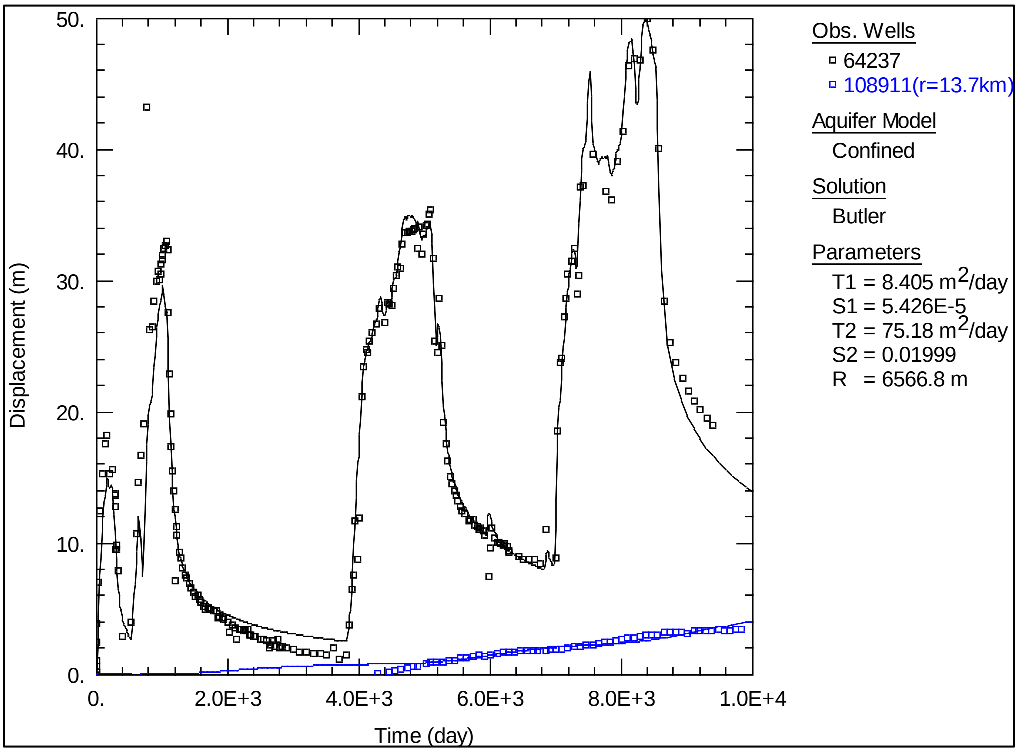


Figure 34: Butler two zone model for rapid response bore 64237 and subdued response bore 108914

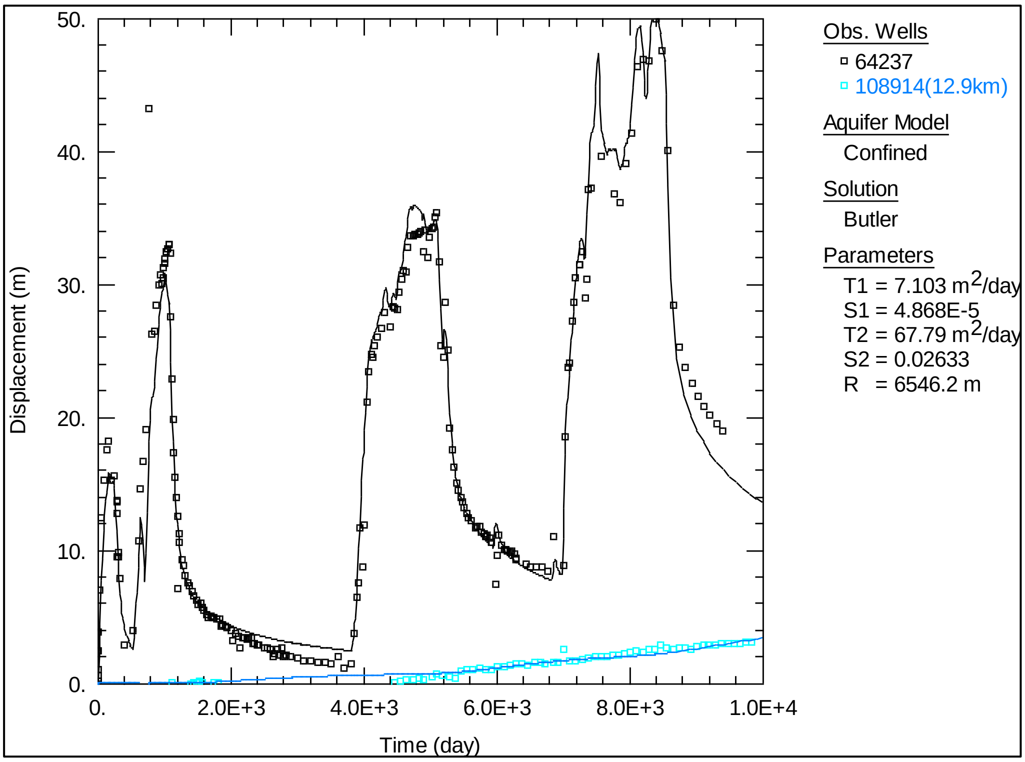


Figure 35: Butler two zone model for rapid response bore 64237 and subdued response bore 108915

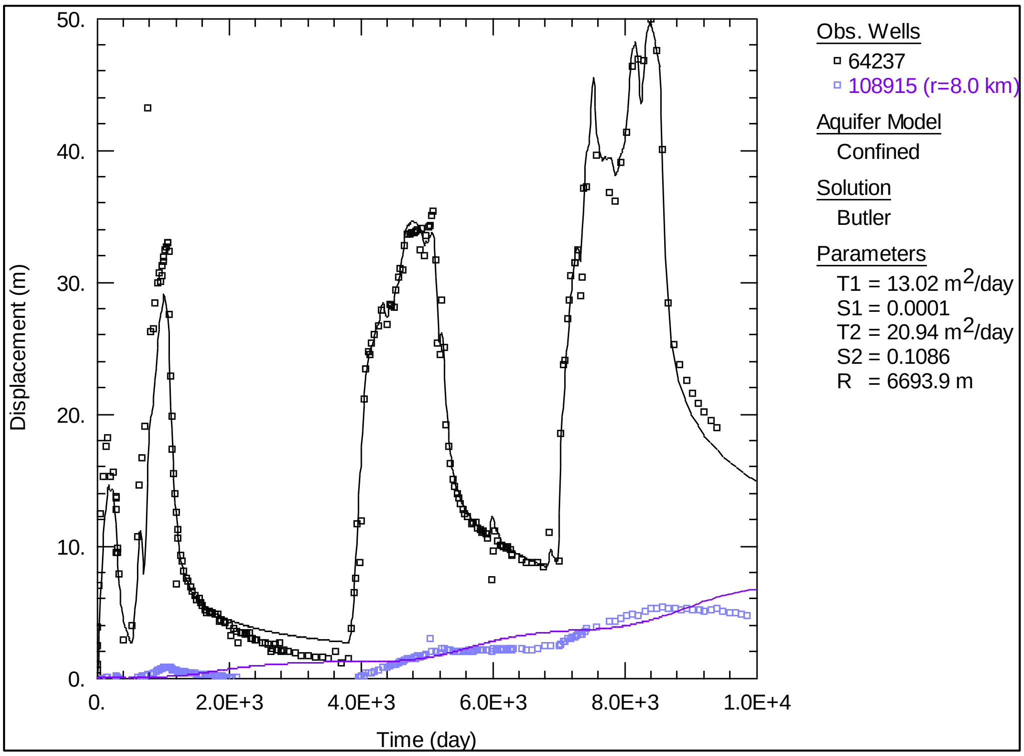
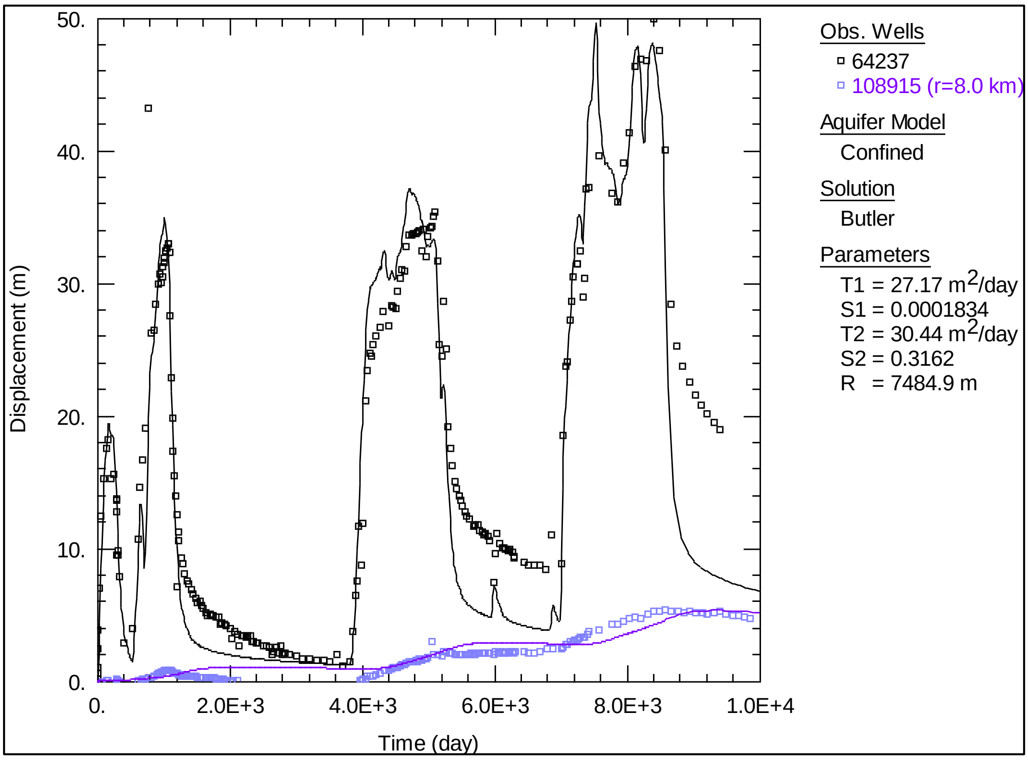


Figure 36: Butler two zone model for rapid response bore 64237 and subdued response bore 108915, with preferred match to 108915



2.5 Comparison with calibrated numerical model

The Butler two zone model that provided the best fit to most of the rapid and subdued bores (64229-64240 model, Table 2) compares very well with observed drawdown at the sites that were used to calibrate the current numerical model (Figure 37 to Figure 39). Although the Butler model matches significantly better to the observed data than the numerical model (for most of the observation bores reviewed in this study), it does not incorporate all of the complexity of the local and regional hydrogeology, so it should not be used as a direct substitute for the numerical model. However, it does indicate that the conceptual model on which the numerical model is based should be reviewed and, if possible, revised.

Due to the highly complex nature of the hydrogeology in the project area it is recommended that refinement of the conceptual model, for the entire model area or where the numerical model calibrates poorly with observed data, be undertaken before any attempt is made to refine the current numerical or build a new numerical model.

A suggested approach is given below:

1. Identify suitable analytical model that fits to observed data for areas not addressed in this report where the numerical model fits poorly to observed data (ie similar process to the assessment in this report)
2. Build a simple numerical model or models to replicate the analytical models including the Butler model used in this assessment
3. Use the simple numerical model(s) to test sensitivity to semi-confined conditions, aquifer boundaries, different shape and sizes of high and low transmissivity and storage co-efficient zones
4. Gradually add complexity to the simple numerical model(s) to more closely resemble the physical hydrogeology of the aquifer system
5. Rebuild and recalibrate a detailed numerical model based on the outcomes of the simple numerical model(s).

Figure 37: Modelled and observed drawdown at bore 64237

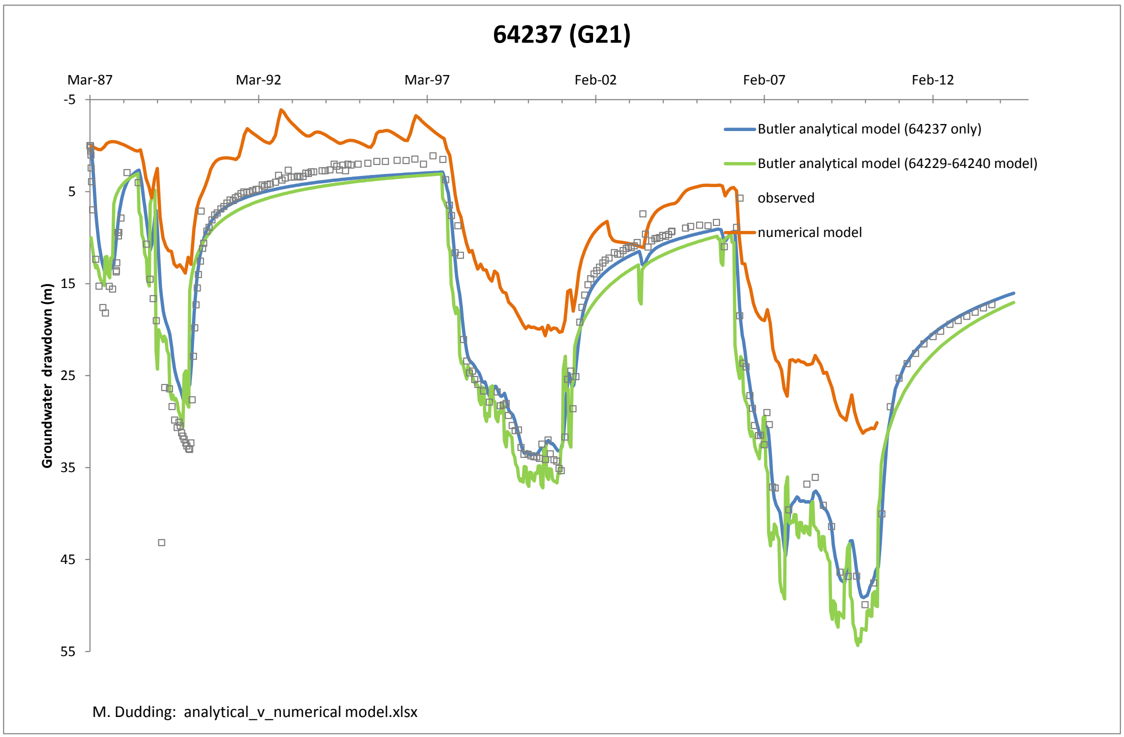


Figure 38: Modelled and observed drawdown at bore 64227

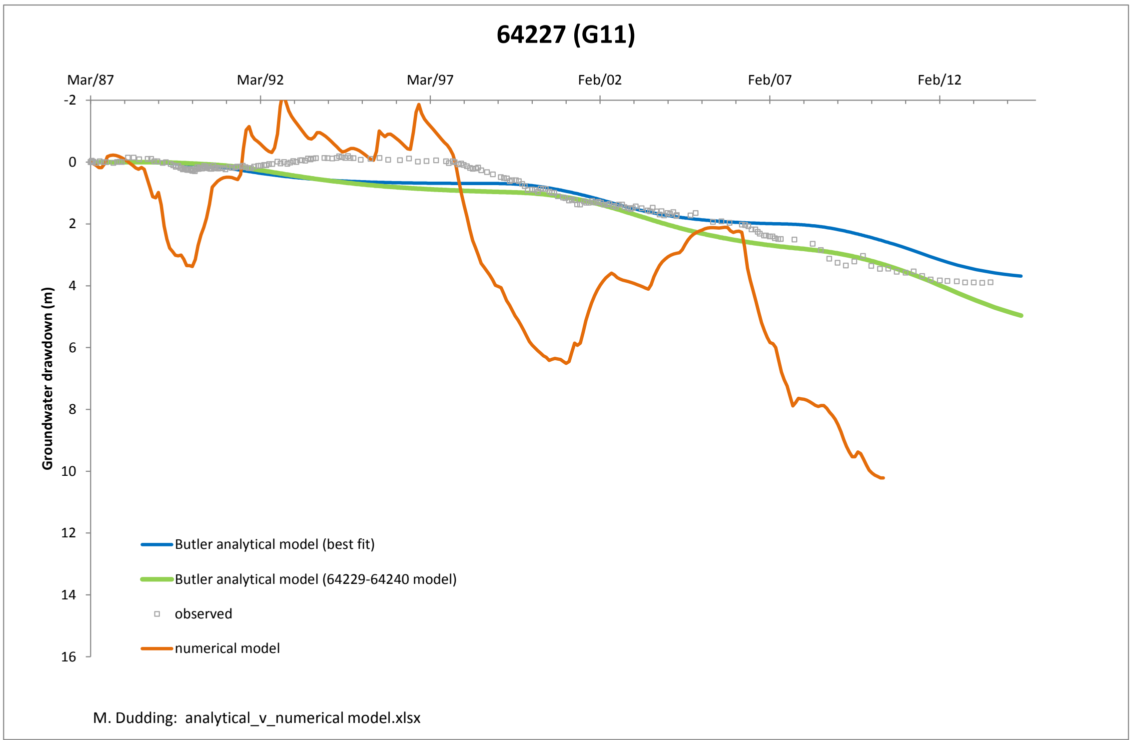
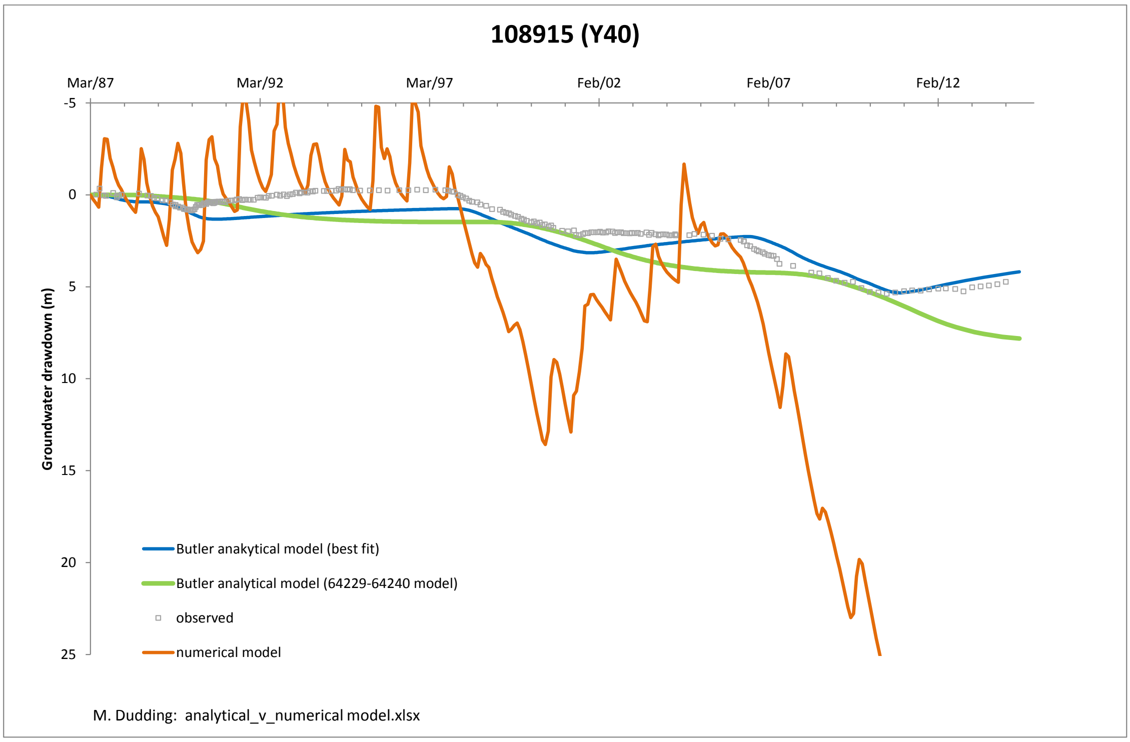


Figure 39: Modelled and observed drawdown at bore 108915



3 North East Boundary

3.1 Observation bores

A total of 17 observation bores located north of the bore field were used in this analysis (Figure 40).

Only three observation bores, 56055, 50056, and 69497 are located north of the fault. Bore 56055 has a continuous water level record between 1989 and 2014, whereas bores 50065 and 69497 only have water level records between 1986 and 1992, and 2000 and 2014 respectively. Drawdown cannot be calculated for bore 69497 due to the water level record commencing 13 years after the start of pumping in 1987. However, comparison of groundwater elevation with bore 56055 indicates that water levels in bore 69497 are likely to have risen since 1987 and hence, there has been no drawdown (Figure 41).

Figure 40: Location of observation bores used in drawdown analysis and approximate location of the Birregurra-Colac Fault, and the Bambra Fault

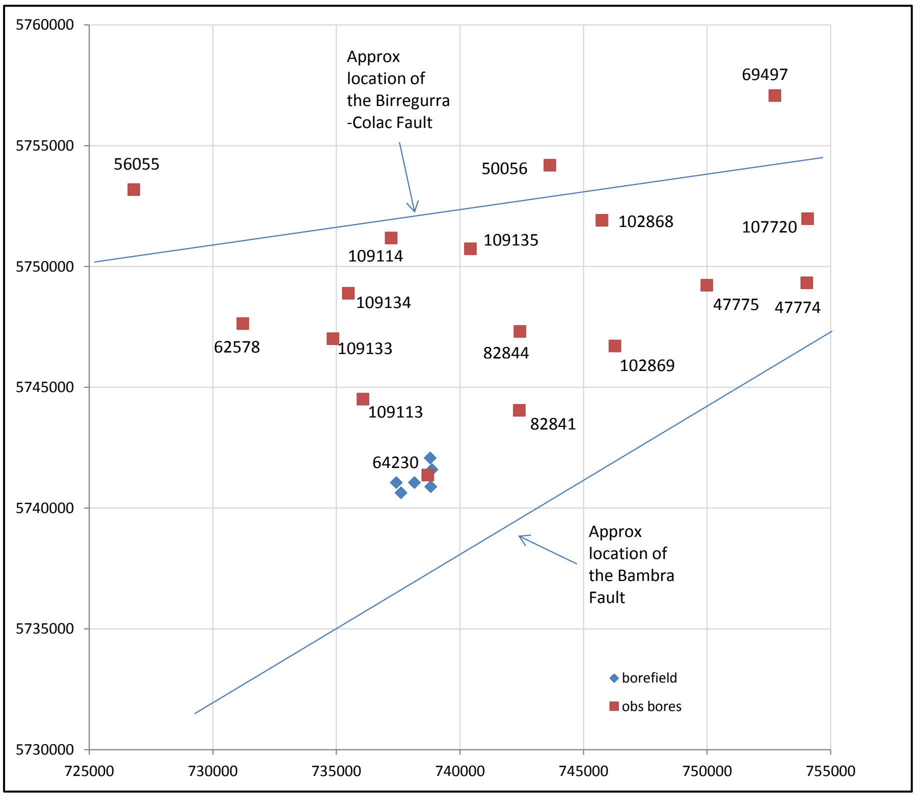
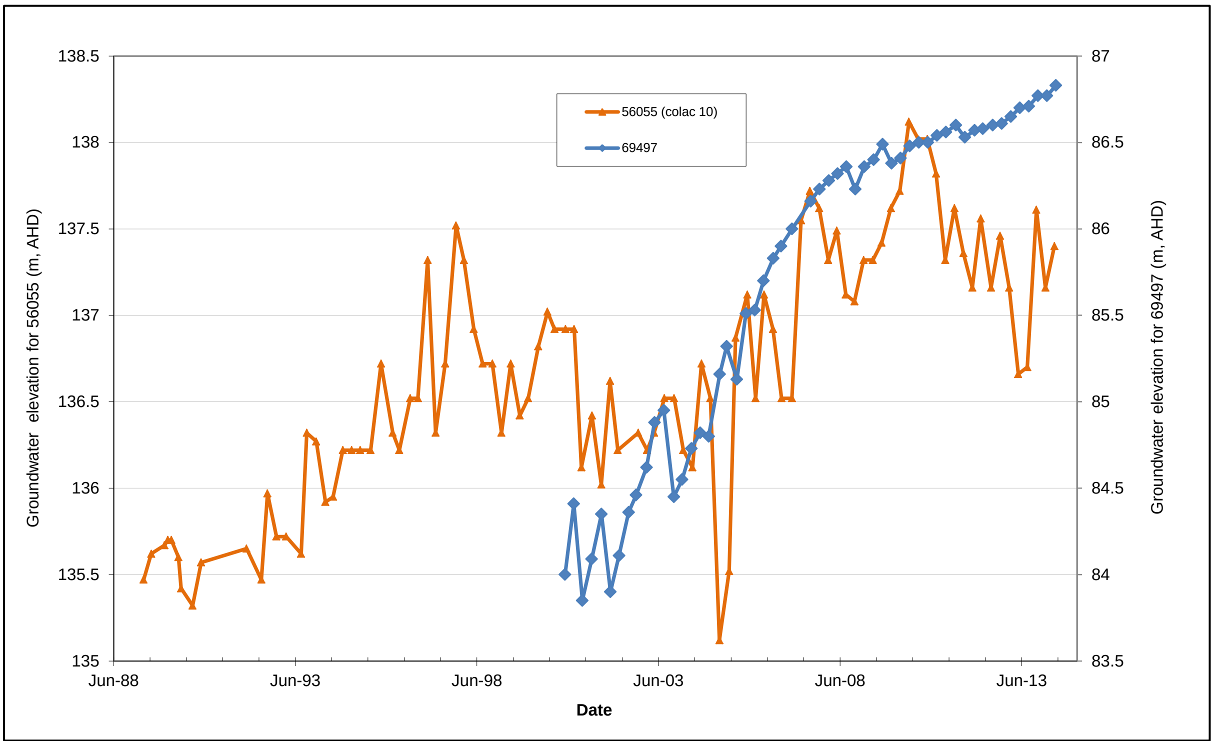


Figure 41: Groundwater elevation for observation bores 56055 and 69497 on the north side of the Birregurra-Colac Fault



3.2 Response to Pumping

All the observation bores on the south side of the fault display a rapid response to pumping at the bore field (Figure 42) compared to the subdued or absence of drawdown on the north side of the fault (Figure 43 and Table 3).

During the 1st period of pumping between 1987 and 1990 the subdued response is due to drawdown not having extended a sufficient distance from the bore field (Figure 44. Note: the 864 day period was chosen because this is when bore 50065 was monitored). However, as pumping continues the extent of drawdown extends beyond the radial distance to the fault in observation bores located south of the fault (eg at the end of the 3rd period of pumping between 2006 and 2010, Figure 45). This suggests that the fault may be restricting drawdown reaching the observation bores on the north side of the fault. However, at the end of the 3rd period of pumping drawdown to the north-west does not reach the fault, so the absence of drawdown on the north side of the fault (at bore 56055) cannot be interpreted as the fault restricting drawdown (Figure 46). To the North and North East drawdown to the south of the fault does appear to extend beyond the distance to bore 69497 located on the north side of the fault (Figure 46). Although this implies that the fault does restrict drawdown the difference between the expected drawdown (log-linear curve on Figure 46) and the observed drawdown at bore 69497 is similar for bores on the south side of the fault, so the absence of drawdown may not be due to the fault but just anisotropy within the aquifer.

Bores 56055 and 69497 have rising water level trend compared to bores on the south side of the fault which have a general falling tend (except for the most recent period of recovery after the 3rd period of pumping) which may also indicate some sort of restriction in groundwater flow across the fault.

Contour plots of drawdown, however, tend to indicate that the variability of drawdown on the south side of the fault is due to anisotropy and the absence of drawdown on the north side of the fault is due to the fault restricting the propagation of drawdown. However, due to the limited number of bores and drawdown data on the north side of the fault it is not clear whether the fault is acting as a complete or partial barrier to drawdown. The current interpretation of drawdown indicates that the fault is acting as a partial barrier to drawdown.

Drilling and monitoring a new bore on the north side of the fault would assist significantly in evaluating the degree of hydraulic connection across the fault, but may require a lengthy period of monitoring data (eg years). Given the high cost of drilling a more suitable approach could be a search for groundwater level data from private bores 50057 and 50061 (which are in close proximity to observation bore 50056) to better determine current groundwater level on the north side of the Colac-Birregurra fault. If historical data could also be found then this could be analysed using methods similar to those applied in this assessment to evaluate the degree of transmissivity reduction across the fault. Drilling a pumping bore on the north or south side of the fault and conducting a pumping test and observing drawdown on the non-pumped side of the fault would provide the highest standard of evaluation of flow across the fault, but this would also have the highest cost.

The following section is an analysis of the drawdown using analytical models to assess the degree to which the fault restricts drawdown.

Figure 42: Hydrographs for observation bores south of the Birregurra-Colac Fault

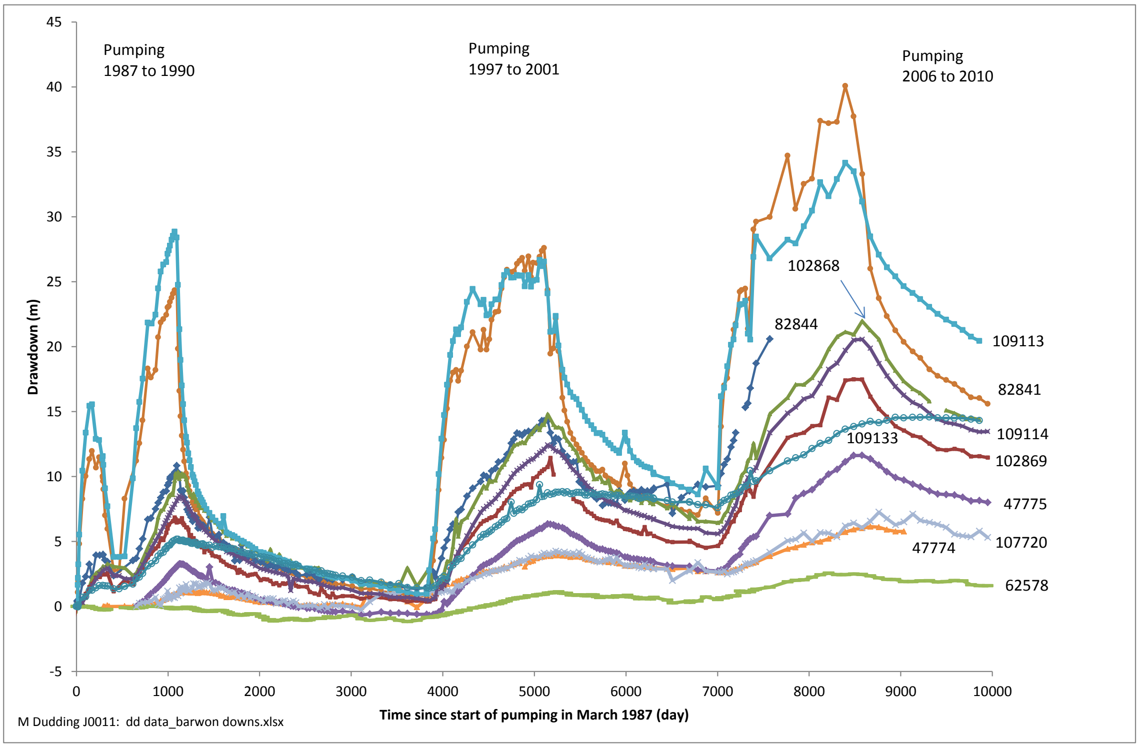


Figure 43: Hydrographs for observation bores north of the Birregurra-Colac Fault. Note bore 69497 not plotted due to water level records starting in November 2000 (Approx. 5000 days after the start of pumping in 1987 ie drawdown as a time series cannot be calculated).

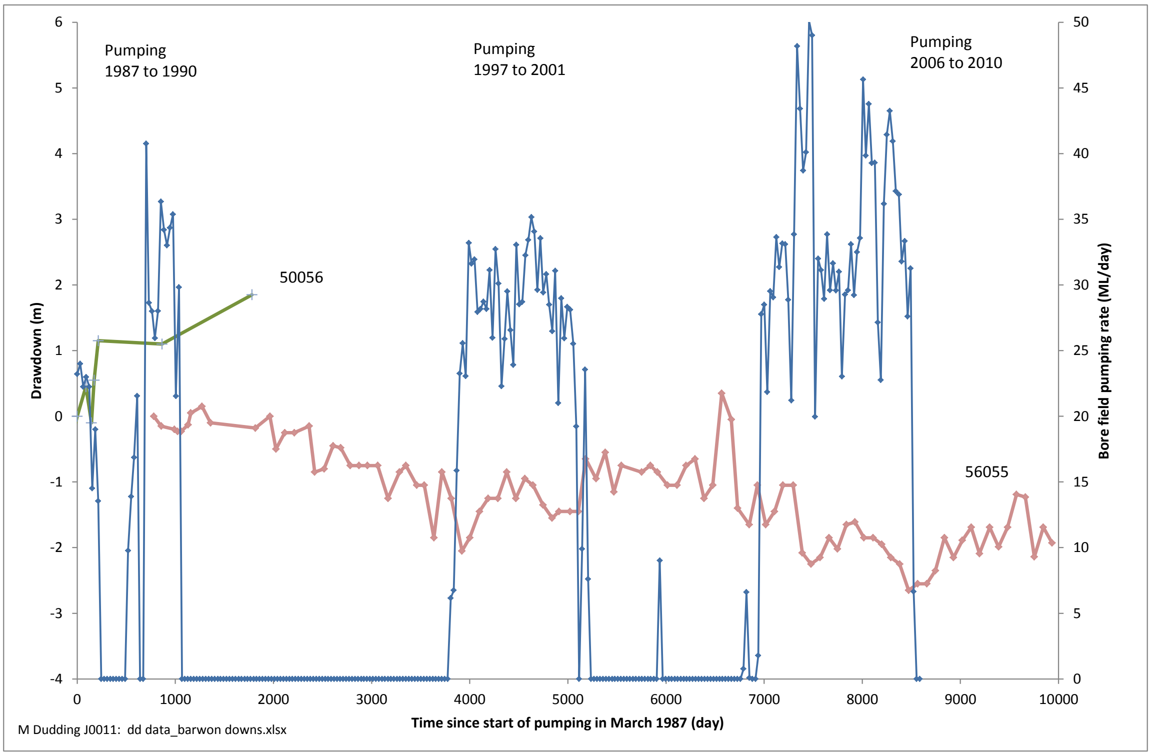


Table 3: Drawdown at each observation bore

Bore ID	Response to pumping	Distance from bore field (km)[1]	Drawdown 864 days after start of the 1st pumping period 1987 to 1990(m)	Drawdown at end of 2nd pumping period 1997 to 2001 (m)	Drawdown at end of 3rd pumping period 2006 to 2010 (m)
South of Fault					
64230	rapid	0.7	51	56[2]	56[2]
109113	rapid	3.7	22.5	26.6 (15%)	33.5
82841	rapid	4.1	18.2	27.6	38
109133	rapid	6.3	3.5	8.5	13.9
82844	rapid	6.4	7.5	14.3	No data
109134	rapid	7.6	2.3	7.0	No data
102869	rapid	8.8	4.5	10.6	17.5
109135	rapid	8.8	6.1	13.1	22.0
109114	rapid	9.2	5.1	12.1	20.5
62578	rapid	9.4	0.0	0.94	2.5
102868	rapid	12.5	5.8	14.0	22.0
47775	rapid	13.3	2.3	7.2	12.6
47774	rapid	16.9	0.3	3.8	6.0
107720	rapid	18.2	0.7	4.1	6.5
North of Fault					
50056	subdued	13.1	1.1	No data	No data
56055	none	16.3	0.0	0.0	0.0
69497	none[2]	20.5	0.0	0.0	0.0

1. Distance is from production bore GW4
2. Estimated. Water levels after 1990 are considered to be unreliable
3. The second pumping period was selected due to some bore no longer being monitored during the 3rd pumping period (2006 to 2010)

Figure 44: Drawdown at increasing distance from the bore field (GW4) during the 1st period of pumping

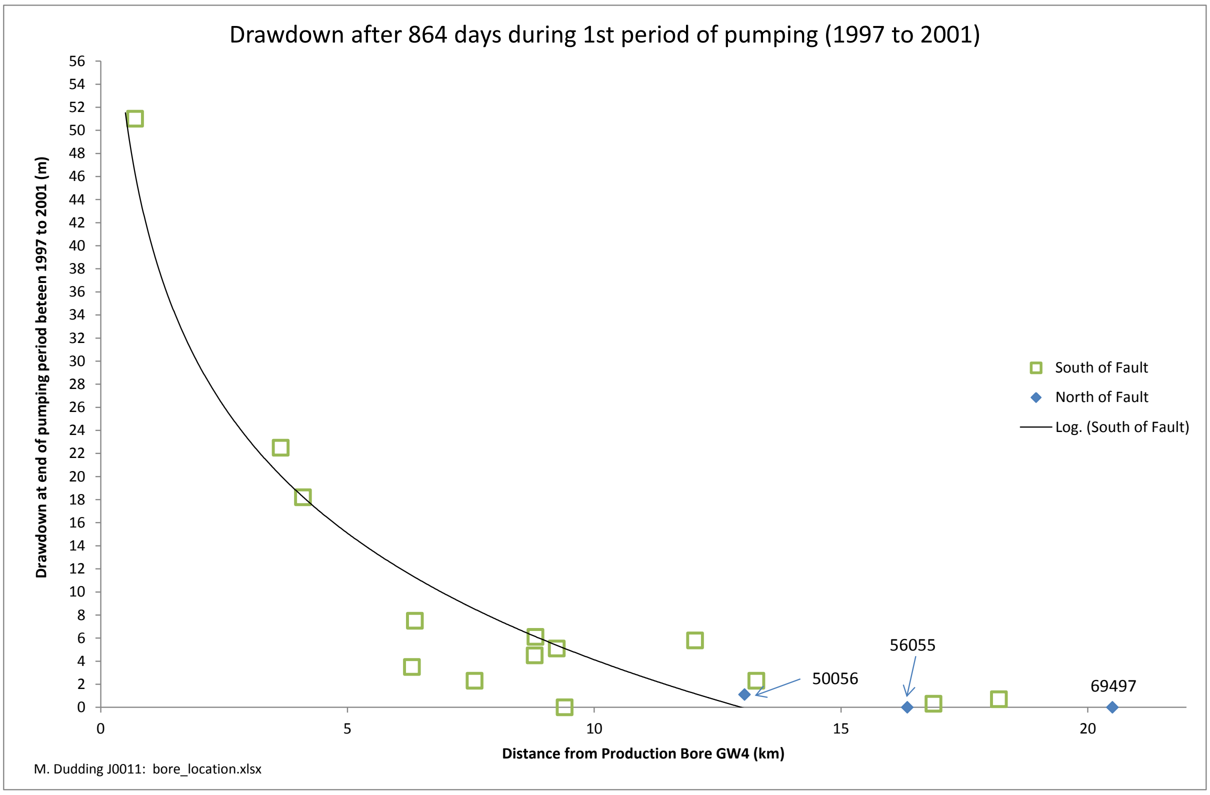


Figure 45: Drawdown at increasing distance from the bore field (GW4) at the end of the 3rd period of pumping

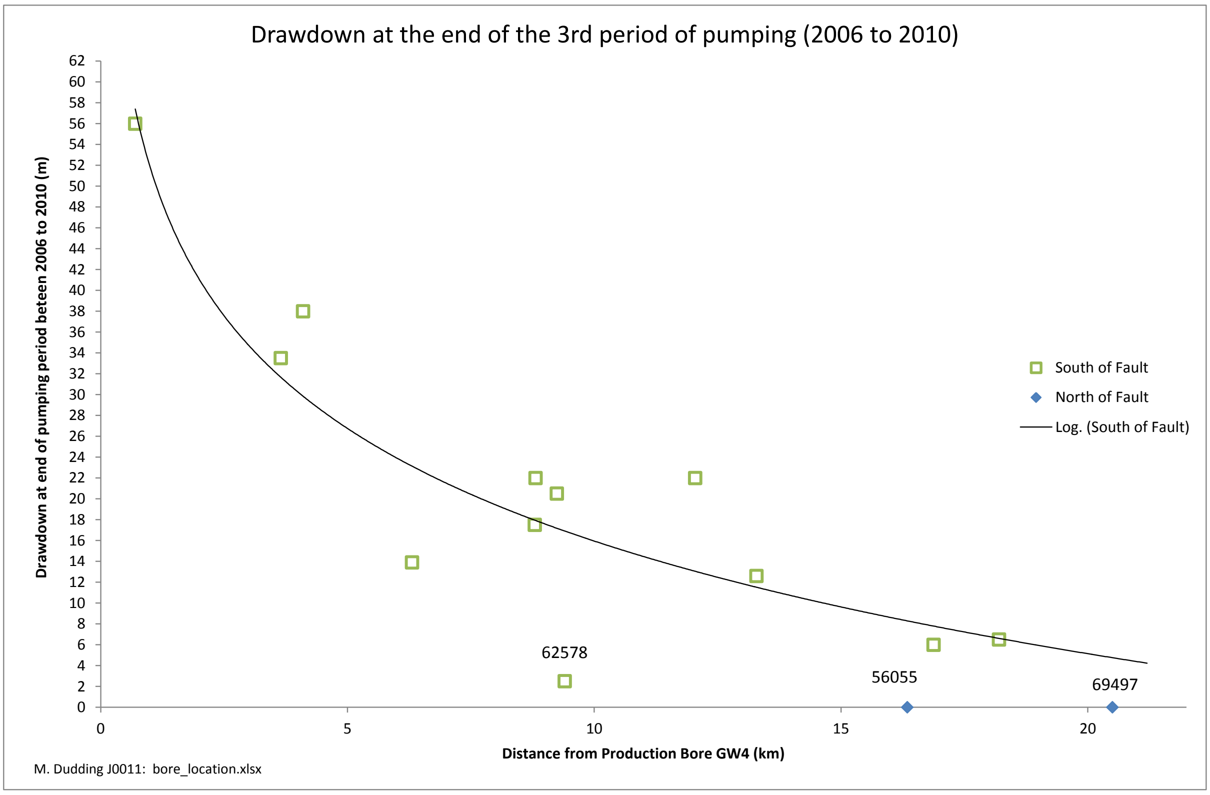


Figure 46: Drawdown at the end of the 3rd period of pumping with bores categorised into those to the north west of the bore field and north and north east of the bore field.

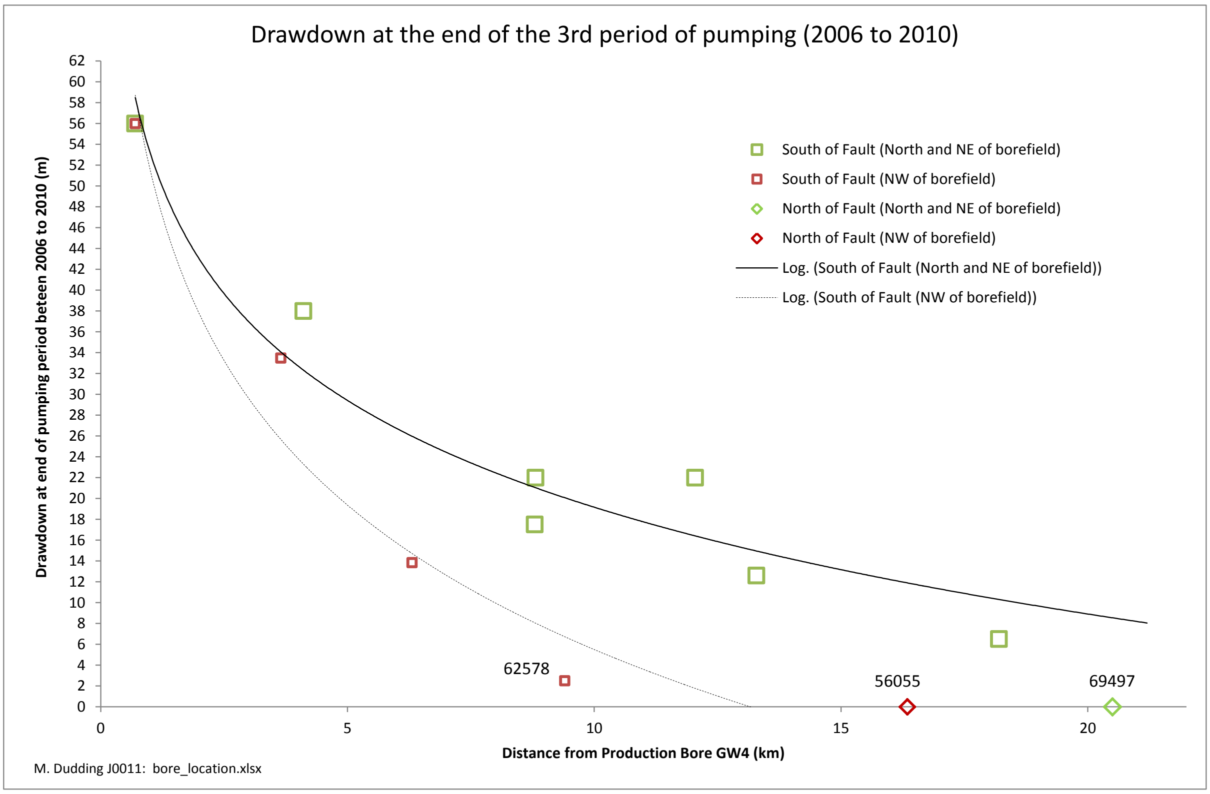


Figure 47: Drawdown in the pumped aquifer 864 days after commencement of pumping in March 1987 (metres). Note: water level are currently monitored in bore 69497 but these are considered to be unreliable, and hence are not used.

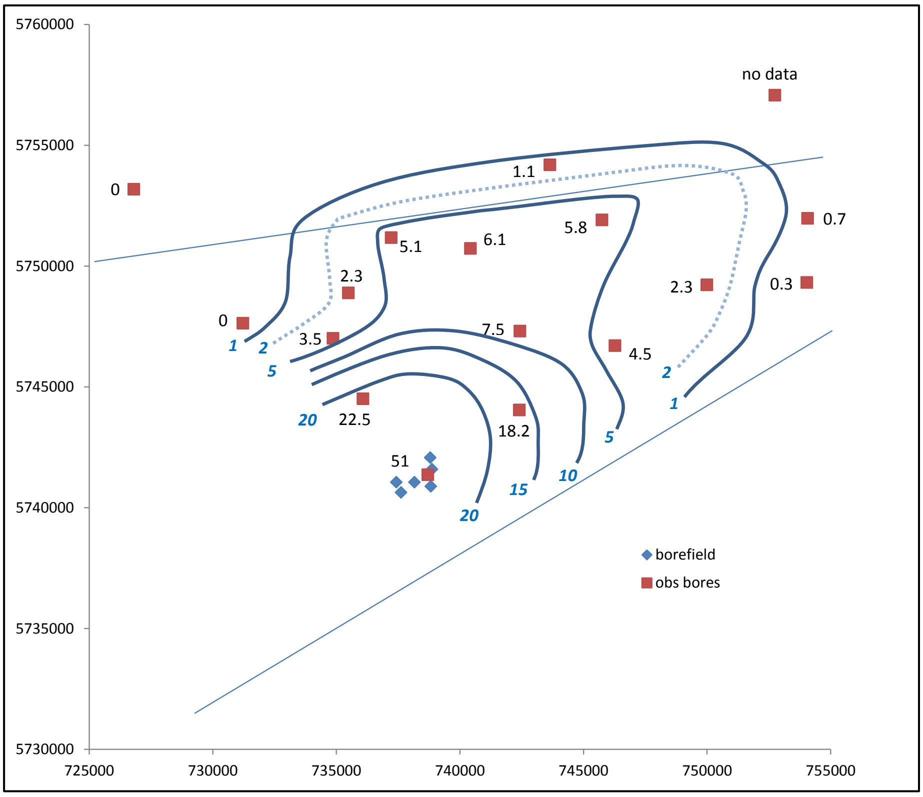


Figure 48: Drawdown in the pumped aquifer between 1987 and 2010 (end of the 3rd pumping cycle) (metres)

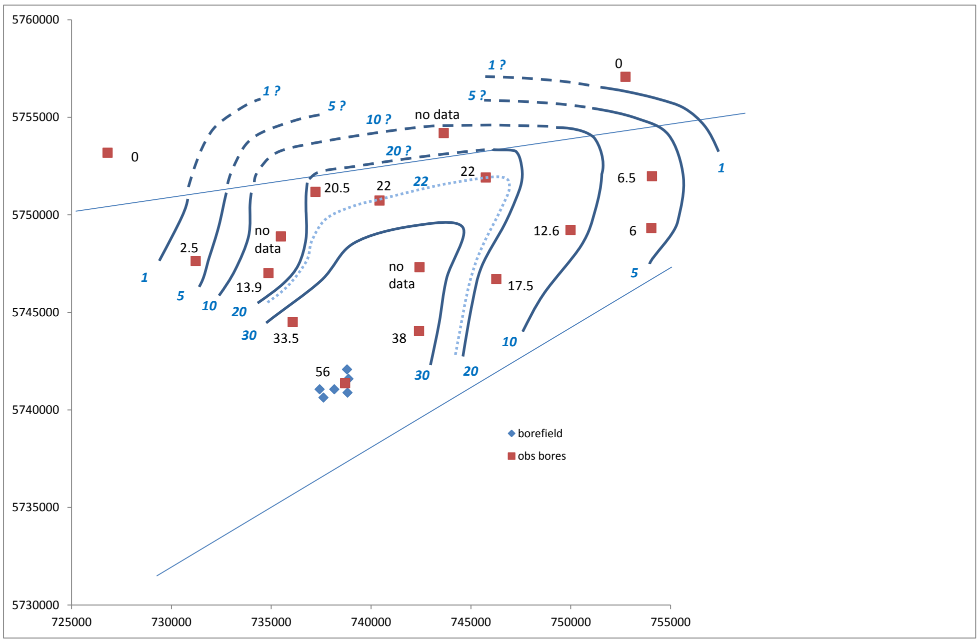
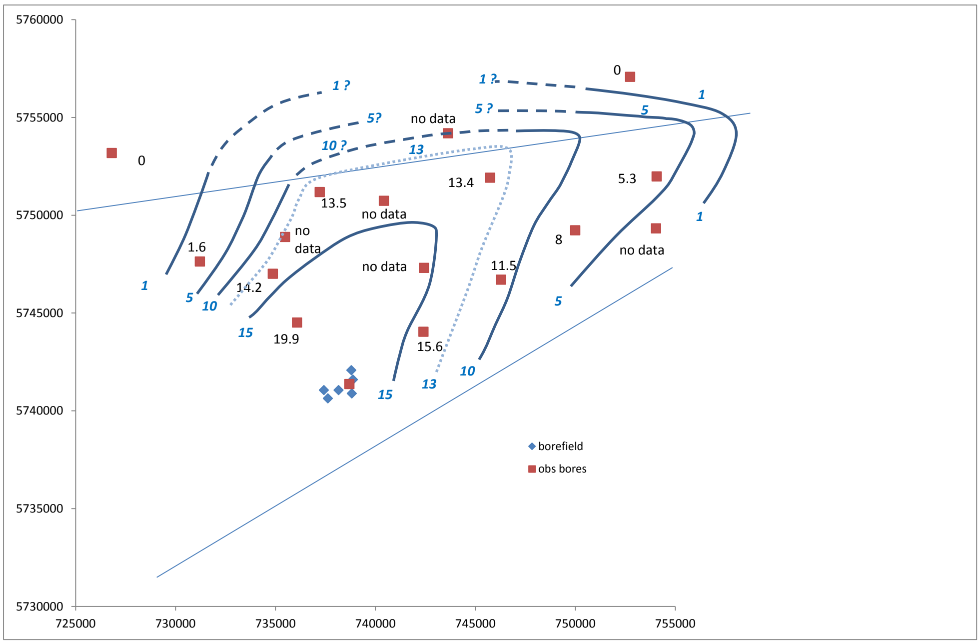


Figure 49: Drawdown in the pumped aquifer between 1987 and May 2014



3.3 Heterogeneous Aquifer

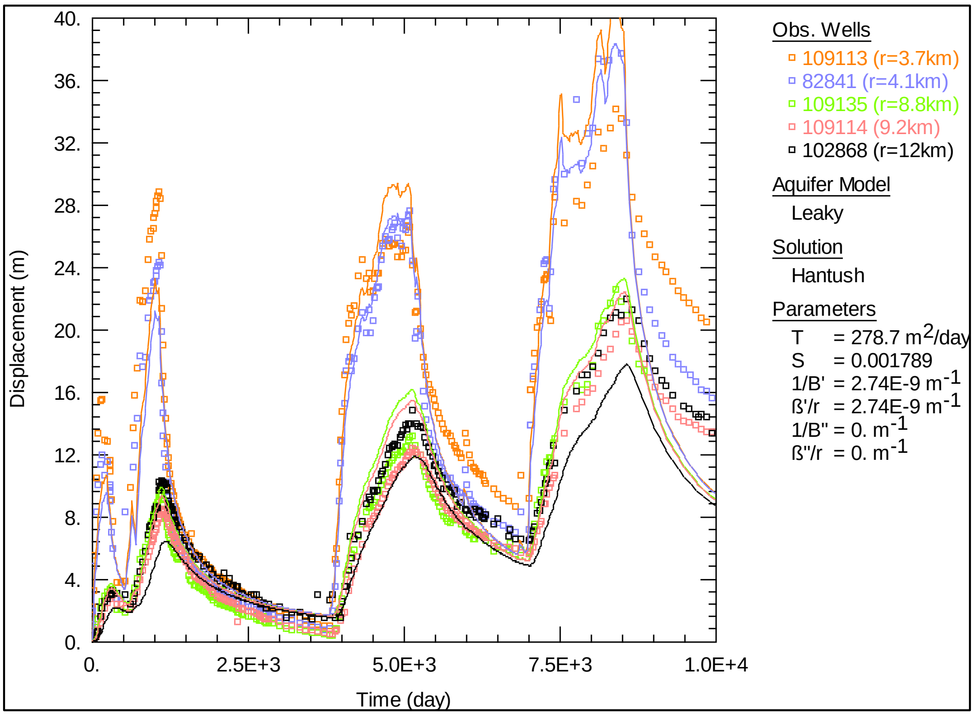
3.3.1 Confined - unbounded

In an heterogeneous aquifer drawdown should propagate uniformly in all directions, and decrease in a uniform manner at increasing distance from the site of pumping. Although plots of drawdown show the aquifer is heterogeneous (eg Figure 49) selecting observation bores located along the main axis of drawdown will simplify the analysis by minimising the variability of drawdown between observation bores located on the south side of the fault. Observation bores 109113, 82841, 109135, 109114, and 102868 have been selected for the analysis because they lie on the main axis of drawdown.

Drawdown from these observation bores fit very well to an heterogeneous model, except for the final period of recovery where drawdown is under-estimated. The under estimation of drawdown may be due to the presence of boundaries, such as the Colac-Birregurra Fault, but may also be due to the Bambra fault, or other factors such as leakage or the presence of unconfined conditions on the Barongarook High and/or east of the Bambra Fault.

The high storage co-efficient tends to indicate there is a strong influence by unconfined conditions or leakage on drawdown.

Figure 50: Confined aquifer model with no boundaries



3.3.2 Confined – bounded

Introducing two boundaries, one representing the Colac-Birregurra Fault and the other representing the Bambra Fault produces a poor fit to the observed data, but does improve the fit to the final recovery period. The two boundary model also requires a very high transmissivity.

Using a single boundary only, representing either the Bambra or the Colac-Birregurra Faults, produces a slightly improved match to the observed data compared to the unbounded model. This suggests that these faults may only be acting as partial barriers to drawdown, and that other factors such as unconfined or semi-confined conditions may have a more significant impact on drawdown.

Figure 51: Confined model with 2 no flow boundaries

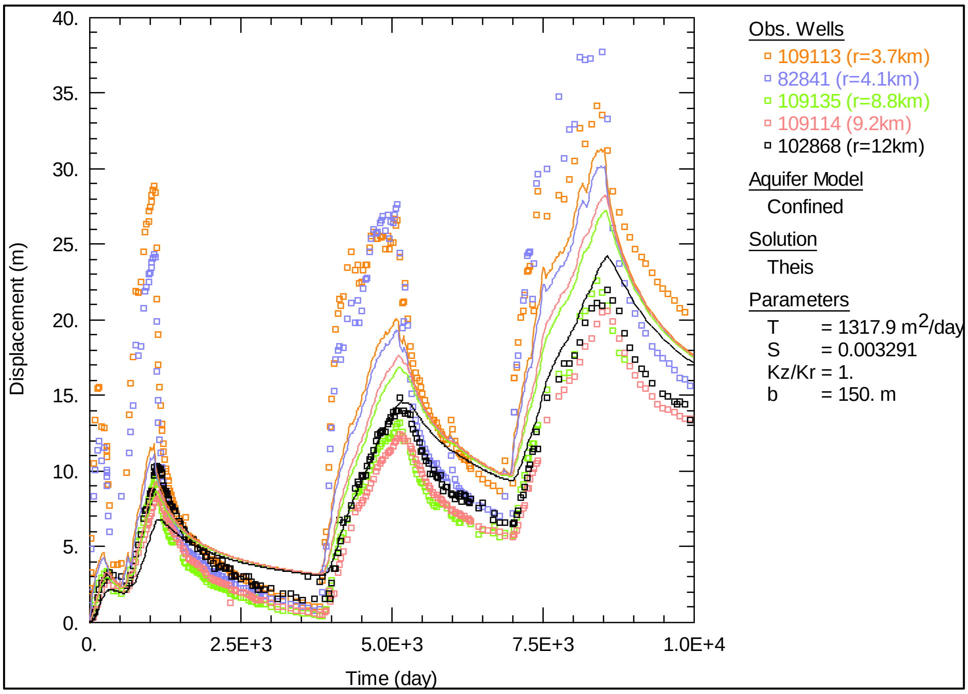


Figure 52: Confined model with 1 no flow boundary only representing the Bambra Fault

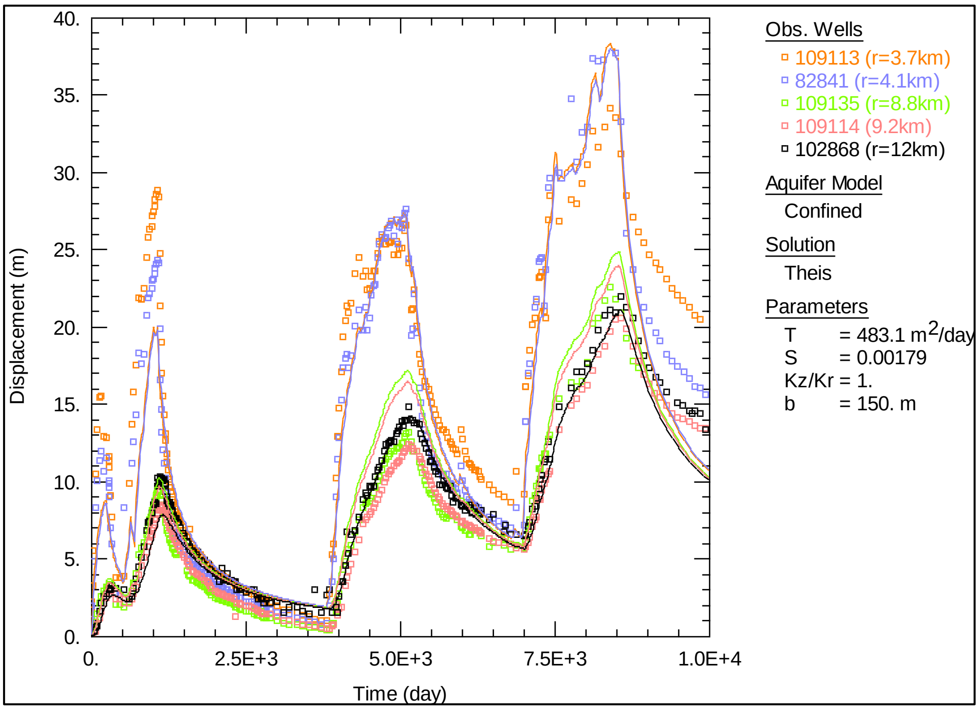
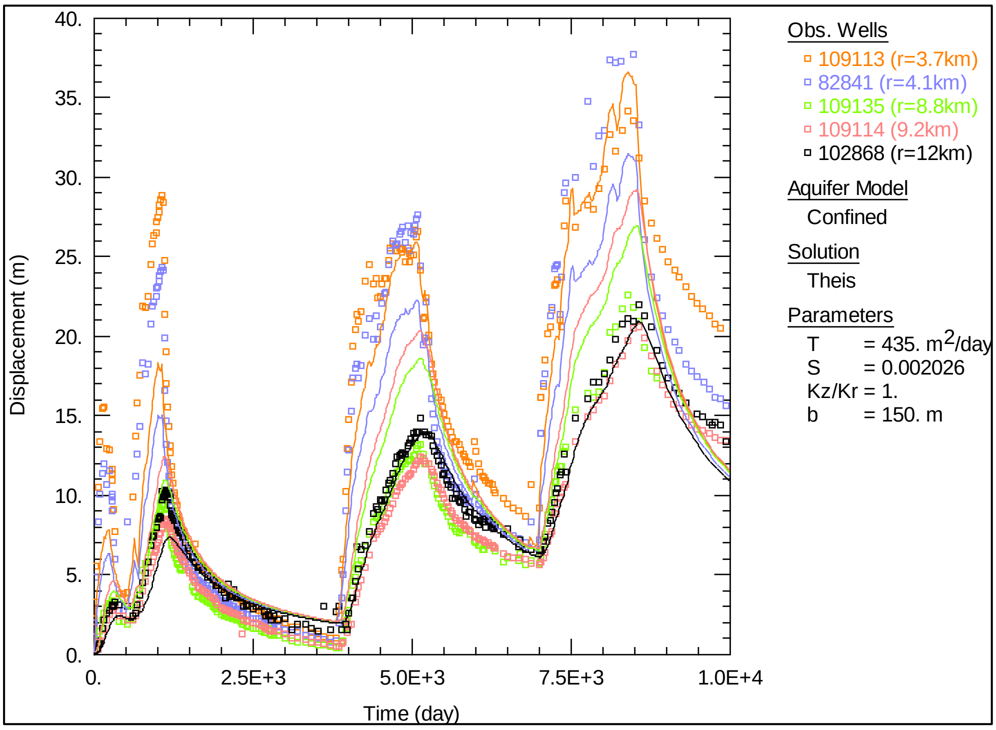


Figure 53: Confined model with 1 no flow boundary only representing the Colac-Birregurra Fault



3.3.3 Semi-confined

The semi-confined model without boundaries produces a very similar result to the confined model. This is not surprising given that the resultant aquitard Kv is 10^{-13} m/day (assuming an aquitard thickness of 400 m).

Introducing two aquifer boundaries significantly improves the match to the observed data. This also results in an increase in the aquitard Kv to 10^{-8} m/day, which indicates leaky aquifer conditions in combination with aquifer boundaries are key contributors to the observed drawdown.

Although there is a very good match to the observed data with the bounded leaky aquifer model, we do know that the aquifer includes regions that are unconfined, and that these regions can also contribute to the slow recovery rate seen after the 2nd and 3rd pumping periods (refer to the analysis for the South West Boundary in Section 2).

To examine the potential for unconfined regions to influence drawdown (and hence, be more significant than aquifer boundaries) an analysis using the Butler model was also undertaken.

Figure 54: Semi- confined aquifer model with no boundaries

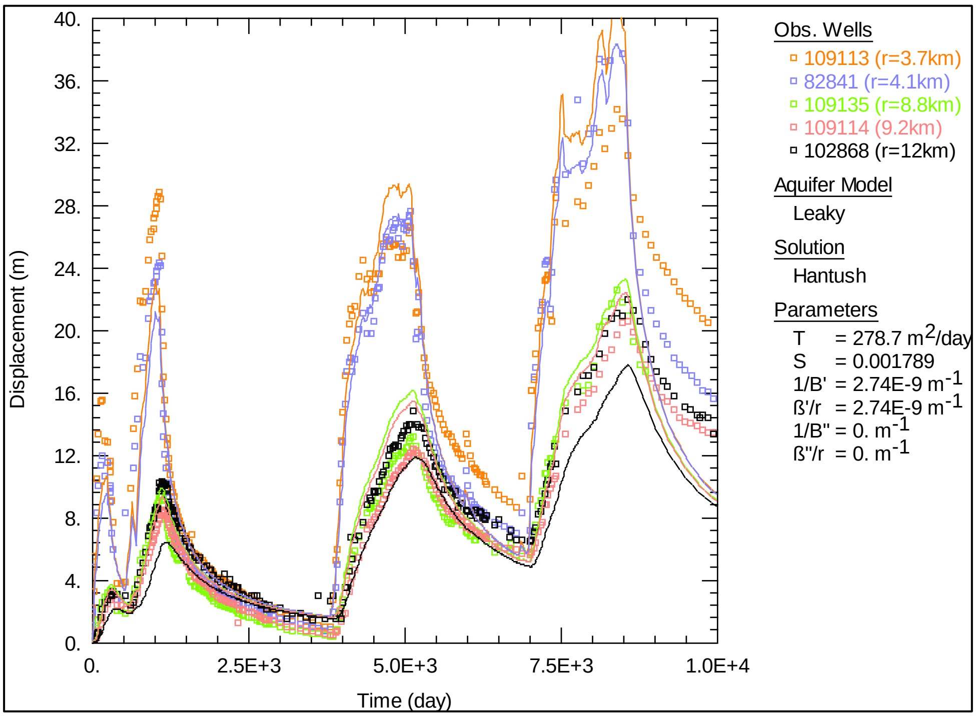
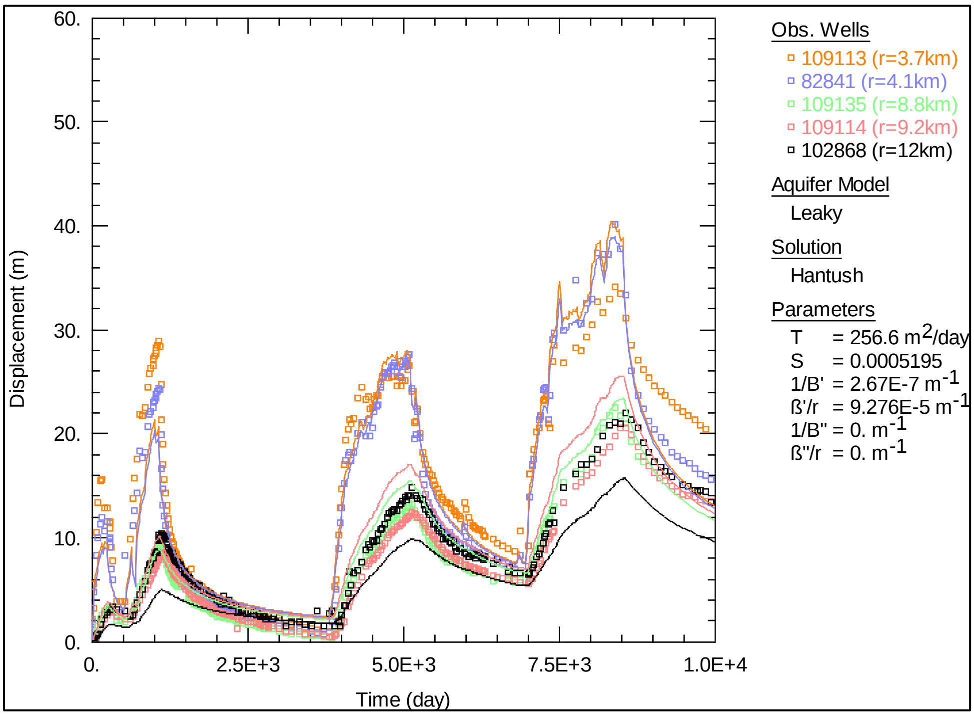


Figure 55: Semi-confined aquifer model with 2 non-flow boundaries



3.4 Heterogeneous Aquifer

The Butler two zone model produces a very good match to the observed data, which is slightly better than that produced by the bounded semi-confined model. The Butler model results in an inner zone with transmissivity and storage co-efficient very similar to the confined unbounded model with a radius of 24 km (approx. distance to the Colac Fault is 15 to 25 km), surrounded by an outer zone with a lower transmissivity (Figure 56).

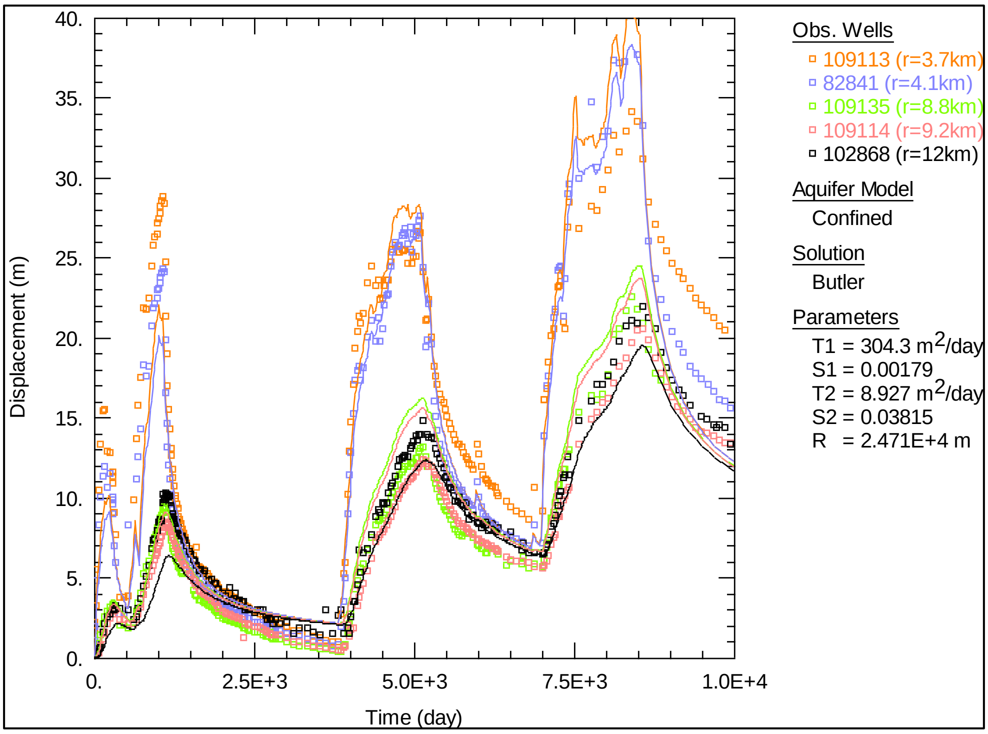
Both the Butler and the semi-confined bounded models indicate that leakage is required to provide a good match to the observed data. The main difference is the Butler model allows the leakage from a zone of lower transmissivity approximately 24 km from the bore field, and the semi-confined model provides leakage from the aquitard.

When taken in combination, the distance drawdown data, drawdown maps, and aquifer analysis indicate that the fault is unlikely to act as a no flow boundary as is currently employed in the numerical model. Not allowing some leakage across the fault may result in higher aquitard Kv values, too high values of transmissivity, or increased specific yield in the unconfined regions of the model.

It is clear that some form of leakage is required, most probably from the aquitard and across the fault.

The relatively poor fit to the last period of recovery may be a result of aquifer boundary, but such a boundary would need to be a much greater distance from the bore field than the Colac –Birregurra and Bambra Faults. The slow recovery after the latest period of pumping, which is particularly marked in bore 109113 during the recovery after the 2nd and 3rd periods of pumping, may also be due to its close proximity to the Barongarook High unconfined area and or lower transmissivity in the NW direction.

Figure 56: Butler two zone heterogeneous model



3.5 Comparison with Numerical Model

The Butler two zone model generally provided a superior fit to the observed water levels compared to the drawdown predicted by the current numerical model (Figure 57 to Figure 61). Although the Butler model matches better to the observed data than the numerical model, it does not incorporate all of the complexity of the local and regional hydrogeology, so it should not be used as a direct substitute for the numerical model. However, it does indicate that the conceptual model on which the numerical model is based should be reviewed and, if possible, revised. Given that the Colac-Birregurra fault is represented as a no-flow boundary in the numerical model (and a zone of reduced transmissivity in the Butler model) and drawdown in the numerical model is generally less than the observed data, suggests that the transmissivity in the numerical model is too high, and/or the storage co-efficient or aquitard leakage is too high.

Due to the highly complex nature of the hydrogeology in the project area it is recommended that refinement of the conceptual model, for the entire model area or where the numerical model calibrates poorly with observed data, be undertaken before any attempt is made to refine the current numerical or build a new numerical model.

A suggested approach is given below:

1. Identify suitable analytical models that fit to observed data for areas not addressed in this report where the numerical model fits poorly to observed data (ie similar process to the assessment in this report)
2. Build a simple numerical model to replicate the analytical models including the Butler model used in this assessment. Alternatively, a simplified version of the current model could also be used although this may be more time consuming and expensive to set up than starting with a new model.
3. Use the simple numerical model to test sensitivity to semi-confined conditions, aquifer boundaries, different shape and sizes of high and low transmissivity and storage co-efficient zones. The process would start with low complexity with respect to hydraulic properties and recharge/discharge (eg very few K and S zones, steady rainfall recharge, steady sw/gw boundaries). The geological complexity should be sufficient to represent the current understanding of bedrock topography, aquifer/aquitard thickness/extent. Nodal density should be highest where the groundwater is most dynamic AND where we are wanting answers (ie sw/gw interaction). The main point is that the model is used to test and refine the hydrogeological conceptualistion.
4. Gradually add complexity to the simple numerical model to more closely resemble the physical hydrogeology of the aquifer system. This would be an iterative process where the model would be used to test different conceptualisations and then in conjunction with other data (eg lithological data) determine what is the most suitable conceptualisation and the numerical model is then refined accordingly.
5. Rebuild and recalibrate a detailed numerical model based on the outcomes of the simple numerical model(s).

Figure 57: Modelled and observed drawdown at bore 82841

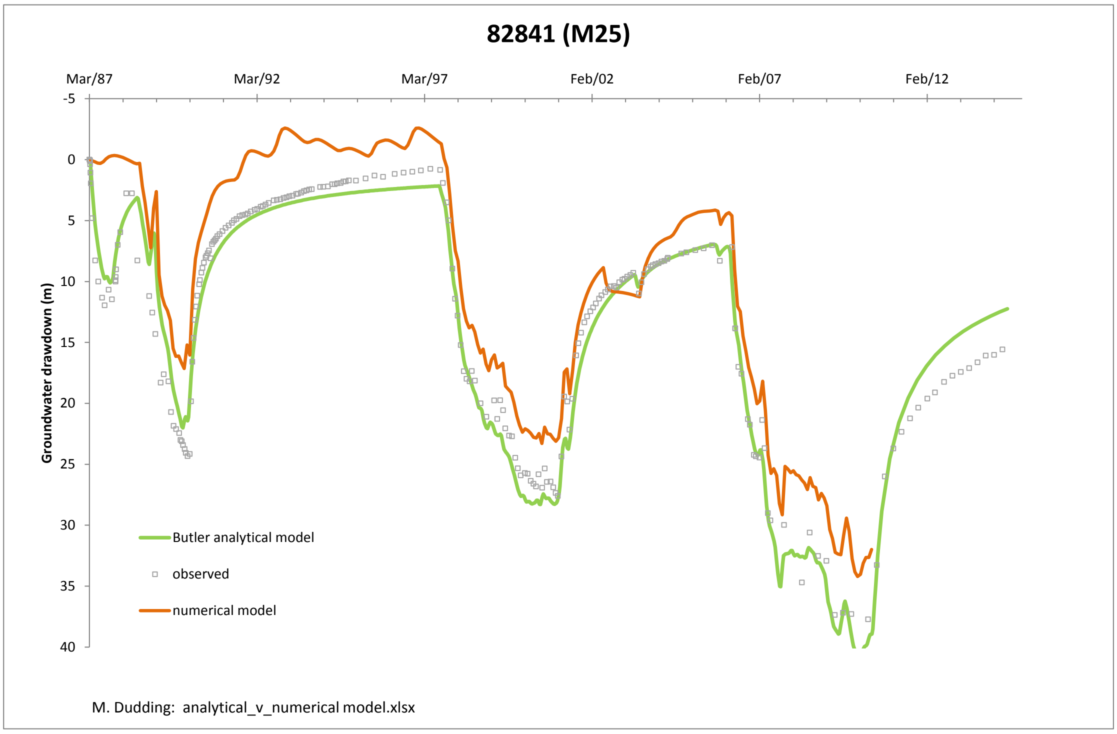


Figure 58: Modelled and observed drawdown at bore 102868

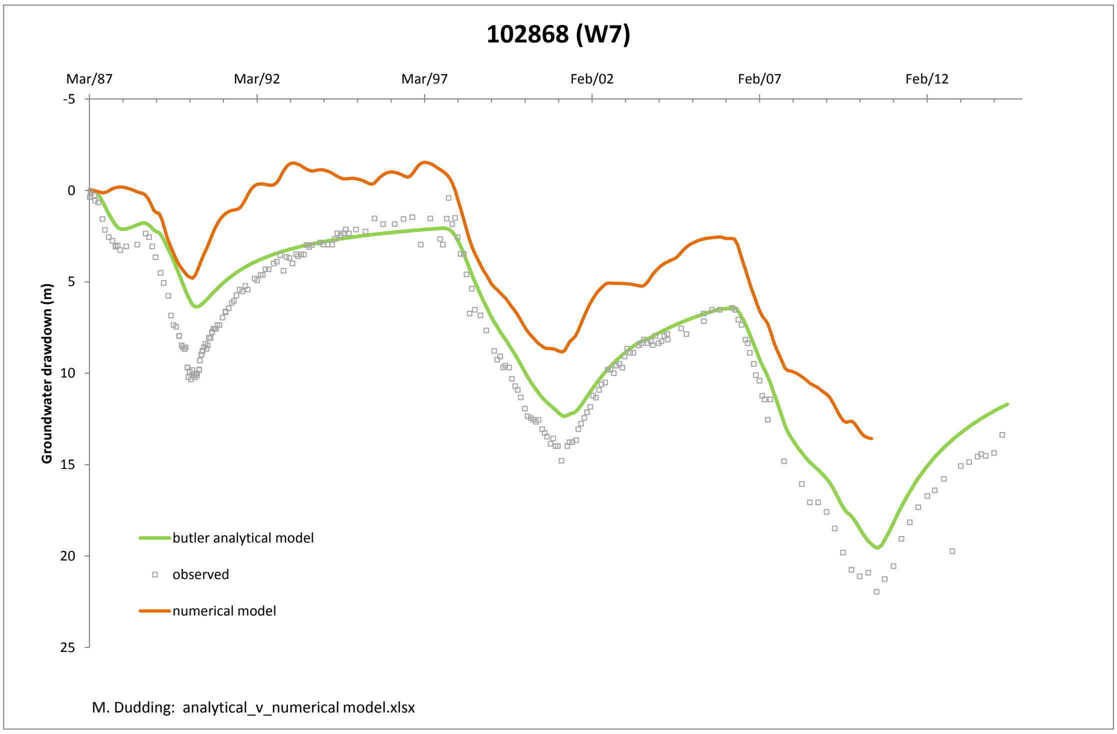


Figure 59: Modelled and observed drawdown at bore 109114

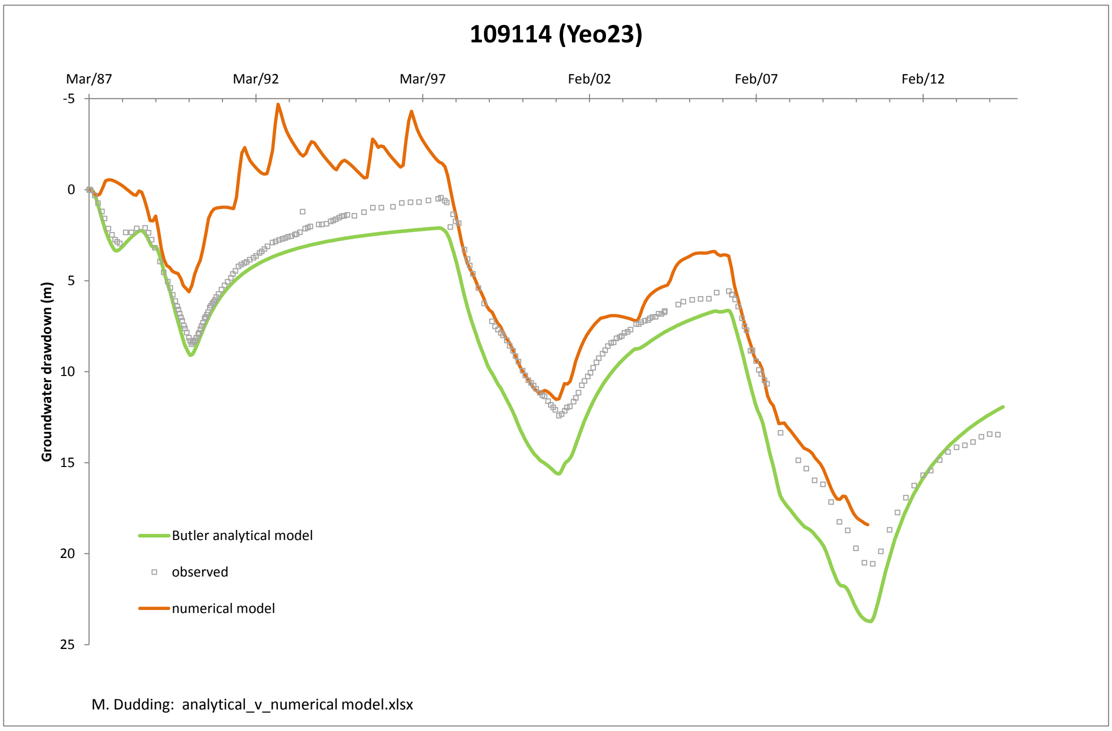


Figure 60: Modelled and observed drawdown at bore 109113

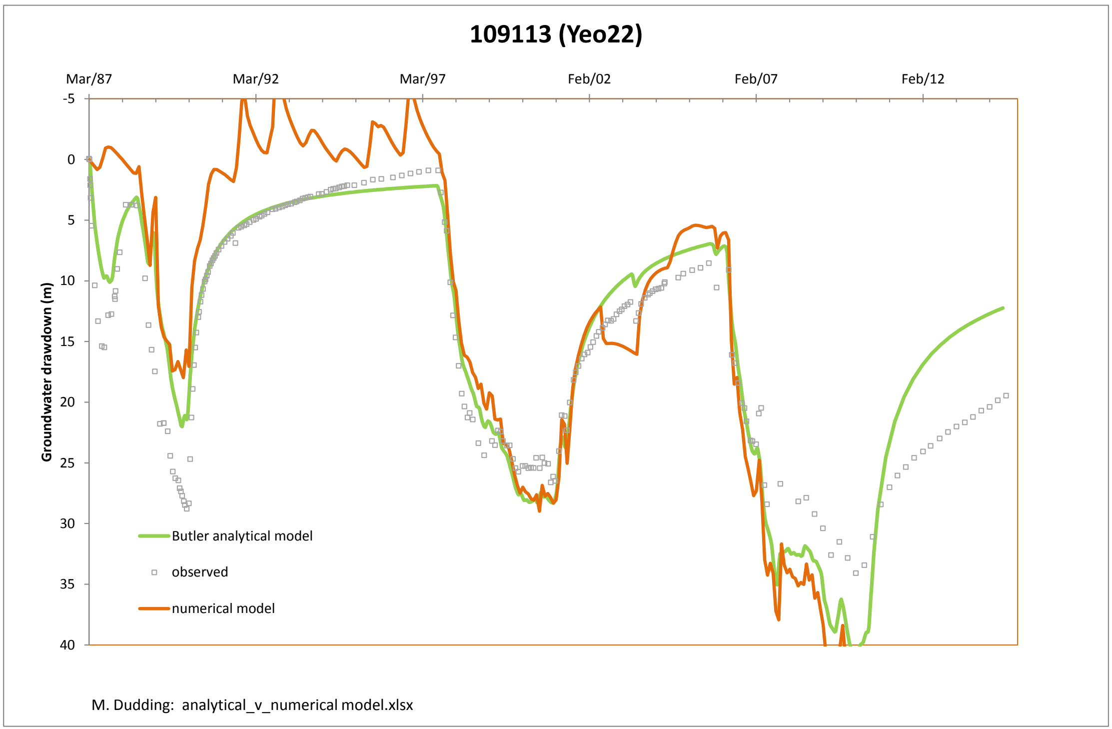
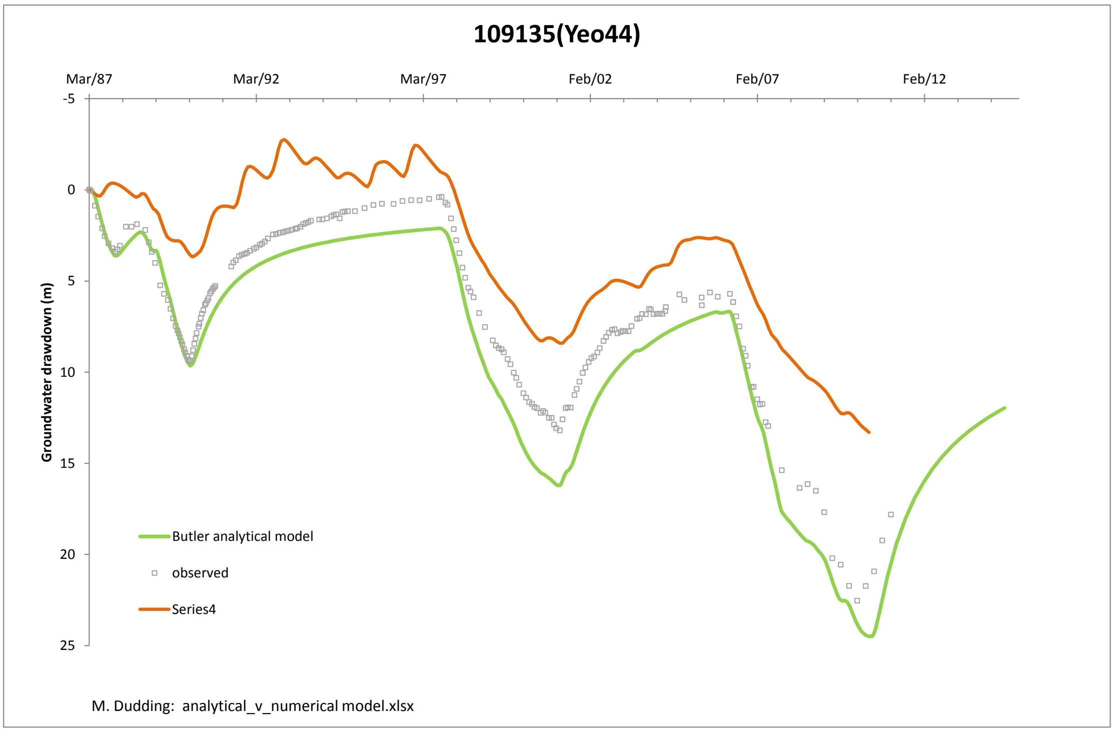


Figure 61: Modelled and observed drawdown at bore 109135



4 Influences on Long Term Drawdown

Over long periods, factors other than groundwater pumping, such as drought, can influence groundwater levels. However, the total change in water level is usually relatively small in the order of 1 to 2 m. At locations that are a large distance from the bore field, drawdown due to drought may be similar or even greater than the direct effects of pumping. As a result it may be difficult to identify the actual amount of drawdown due to pumping. For this assessment it has been assumed that the drawdown observed in the subdued bores is due to pumping, not other factors such as drought. If drought has contributed to some or all of the observed drawdown then this could impact on the conceptual model.

Although it is not the objective of this assessment to identify the influence of non-pumping effects on drawdown, a simple sensitivity test shows that an assumption of zero drawdown in the subdued bores due to pumping (ie the observed drawdown is not due to pumping) can be incorporated within the Butler model by increasing the storage co-efficient of the Zone 2 (and minor adjustments to transmissivity) while maintaining a close match to the rapid response bores (Figure 62to Figure 65).

This doesn't suggest that the observed drawdown is due entirely to drought, but does indicate that the two zone conceptual model is not invalidated by drought effects on drawdown in the subdued bores.

Figure 62: Butler two zone model for rapid response bore 64237 and assuming zero drawdown for subdued response bore 48003

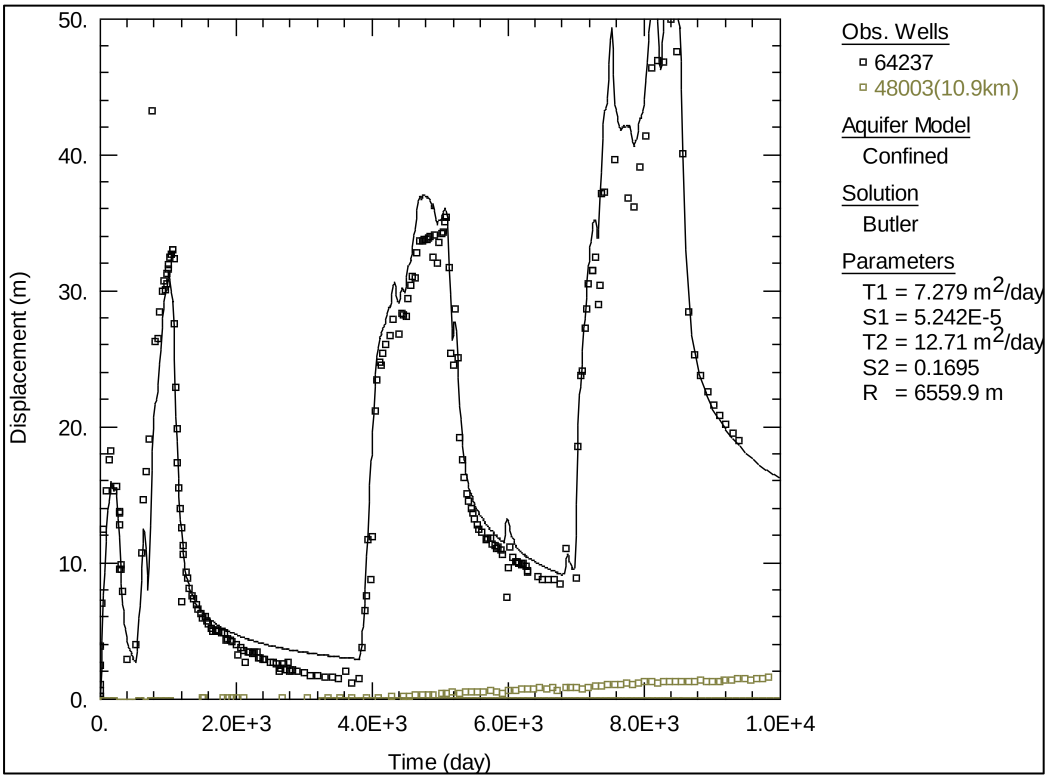


Figure 63: Butler two zone model for rapid response bore 64237 and assuming zero drawdown for subdued response bore 64227

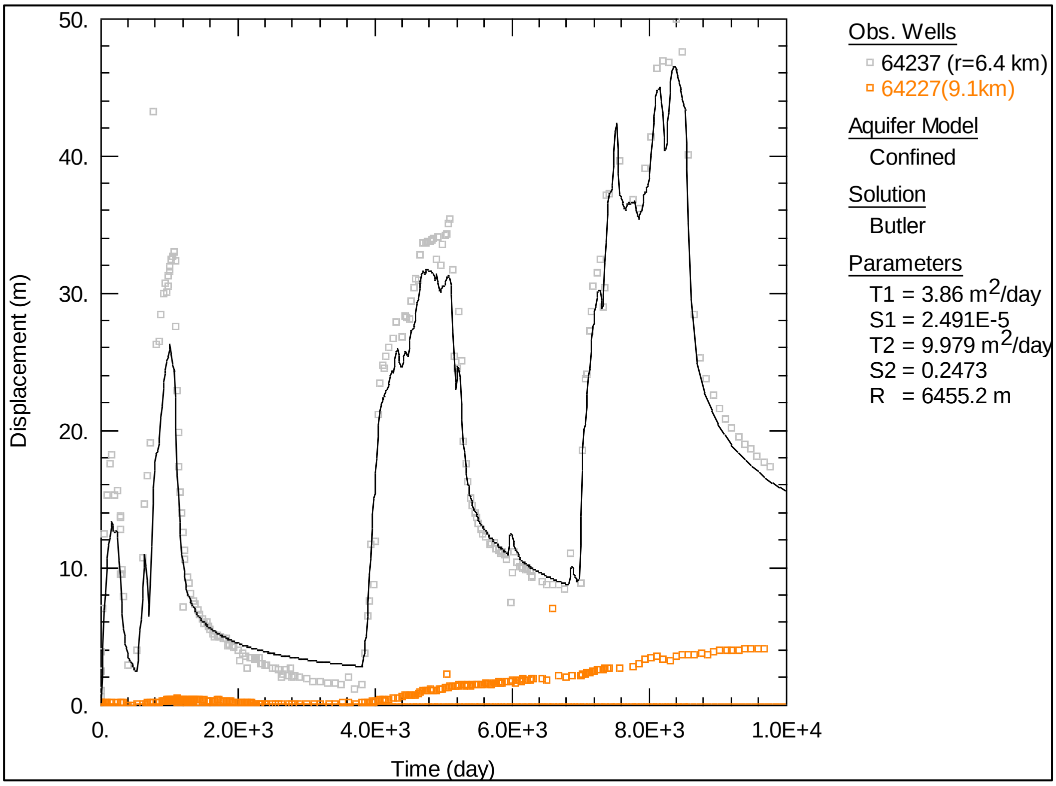


Figure 64: Butler two zone model for rapid response bore 64237 and assuming zero drawdown for subdued response bore 108911

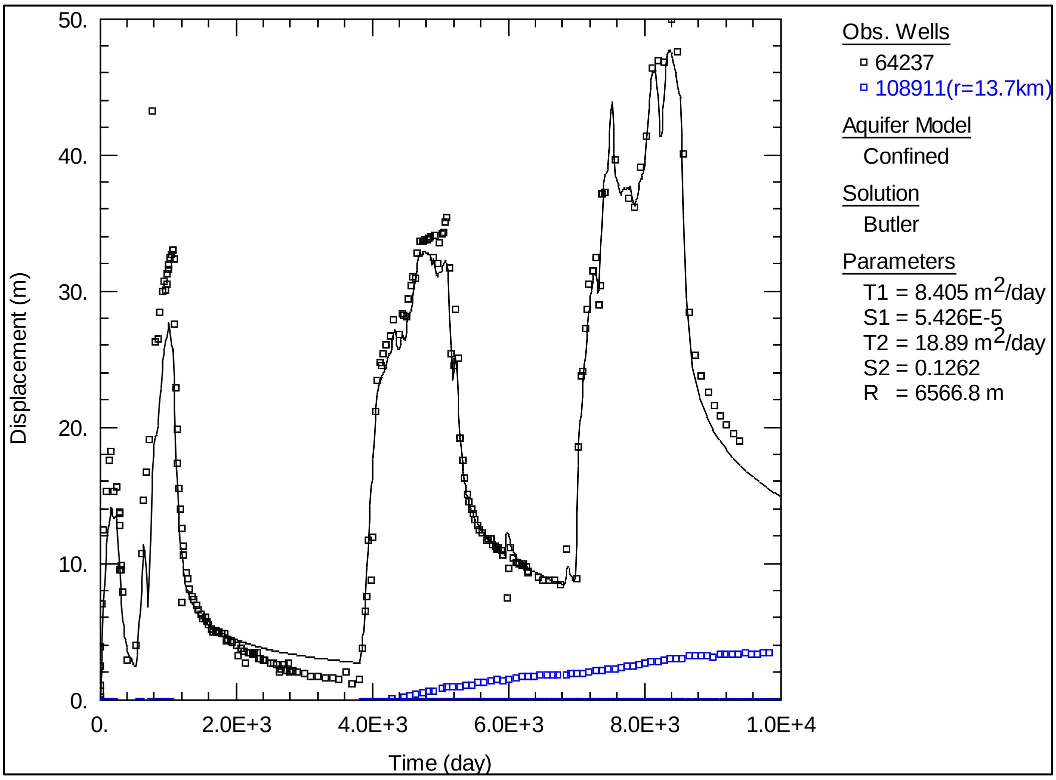
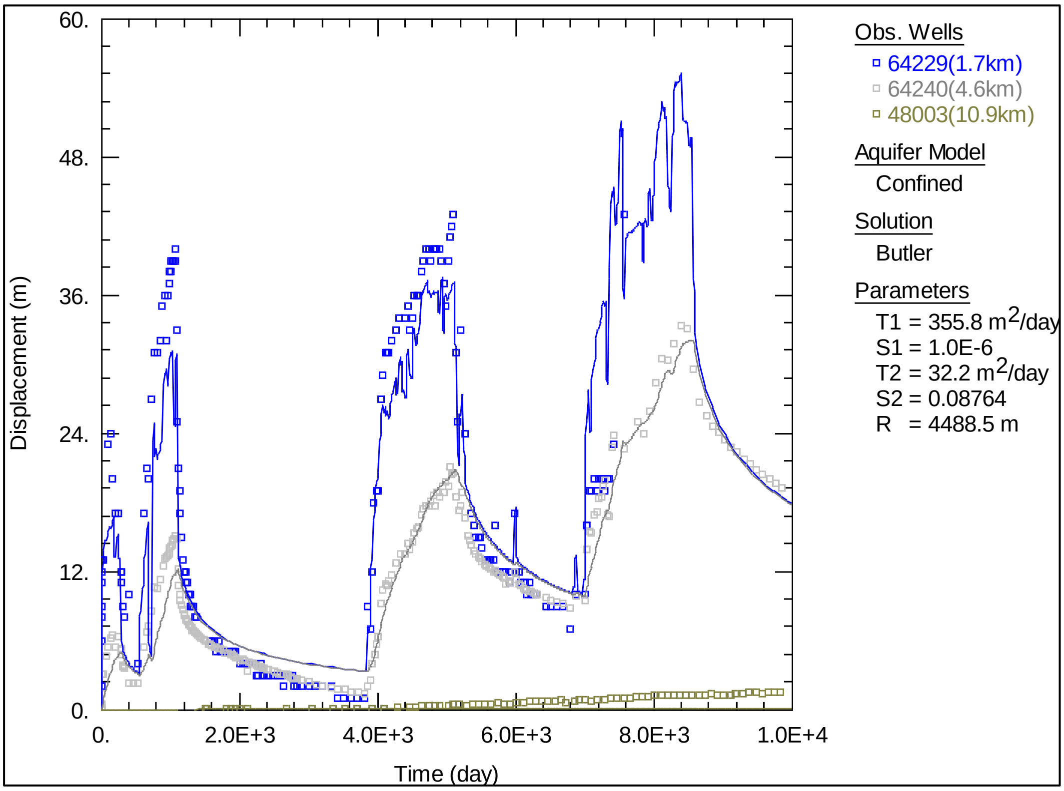


Figure 65: Butler two zone model for rapid response bores 64229 and 64240, and assuming zero drawdown for subdued response bore 108911



5 Conclusions

5.1 South West Boundary

Analysis of drawdown in observation bores located between the bore field and the model boundary indicate that there is some form of barrier to groundwater flow between the Barwon Downs and Gellibrand groundwater sub-basins. This barrier is likely to comprise two components:

- A low transmissivity zone or zones in the confined aquifer, most probably to the west of bore 64237, and
- Areas of high storage co-efficient caused by either unconfined conditions (most probably where the aquifer outcrops on the Barongarook High and to the South East of the Bambra Fault), and/or an area with high leakage rates from the aquitard.

The analysis shows very clearly that aquifer is not uniform in its hydraulic properties (ie transmissivity and storage co-efficient), and is likely to comprise multiple zones of varying transmissivity and storage co-efficient. Transmissivity is likely to be highest near the bore field and lowest in an area around bores 64237 and 64244 but are likely to be highly variable in size and location. The analysis does not rule out areas of high transmissivity existing in the Kawarren-Gellibrand area, as is indicated by pumping tests undertaken in that region during the Gellibrand Dam investigations in the 1970’s and the Newlingrook investigations in 2007 to 2009.

It is clear from previous investigations that the hydrogeology in the region is very complex and this is, in part, reflected in the difficulty in obtaining acceptable calibration of the existing numerical model in the south-western region. Although the analytical models used in this assessment do not fully reflect the complex hydrogeology, the very good match obtained to the Butler two zone model provides a strong basis on which the conceptual model (and ultimately numerical model) should be further developed/refined.

Due to the large depth to the aquifer it isn’t considered cost effective to undertake drilling and field testing to refine the current understanding of aquifer transmissivity. A more cost effective approach would be to re-examine existing data (eg bore lithology logs, bore geophysical logs, and seismic surveys) to improve the current understanding of aquifer and aquitard lithology, and to use simple numerical models to reproduce the Butler analytical model, and then use this model to test sensitivity to semi-confined conditions, unconfined conditions, aquifer boundaries, and aquifer morphology. The outcomes would then be used to inform how the detailed numerical model should be structured.

Before building a simple numerical model a review should be done identifying where the current model has good and poor calibration, to identify whether one or more simple models are required.

Gamma logging existing bores, if not available, would also be a cost effective method of obtaining high quality information on aquifer and aquitard lithology. This would be particularly useful in identifying structure within the aquifer and the aquitard, which could significantly improve our understanding on the potential for semi-confined conditions to be present, and whether the aquifer should be considered to be a single unit or divided into sub-units.

Groundwater flow across the Bambra Fault is also a significant component of the current conceptual model and could have some bearing on how the south-west model boundary is conceptualised. An analysis of leakage across this fault (to the north and south of the bore field) using methods similar to those applied in this report would assist significantly in the development of the conceptual model. Pumping tests are the 'gold standard' for assessing leakage across hydrogeological boundaries, such as faults, but are costly to undertake. A test site was partially prepared (one of the bores has been drilled) for the Newlingrook groundwater investigation to assess hydraulic connection across the Bambra fault Consideration should also be given to undertaking the pumping test that was proposed as part of the Newlingrook project which would provide useful information on how well the unconfined area of the aquifer on the south-eastern side of the Bambra Fault is connected to the confined section of the aquifer.

5.2 North East Boundary

Analysis of drawdown in observation bores located between the bore field and the Colac-Birregurra Fault indicate that the fault is unlikely to act as a no-flow boundary. However, it is likely that there is a significant reduction in transmissivity, possibly as high as 90%, on the north side of the fault.

Given that the Colac-Birregurra fault is represented as a no-flow boundary in the numerical model and drawdown in the numerical model is generally less than the observed data tends to suggest that the transmissivity in the numerical model is too high, and/or the storage co-efficient or aquitard leakage is too high.

6 Recommendations

1. For the south-west boundary area the Butler analytical model be reproduced using a simple numerical model covering the full model area. Use the simple numerical model to further refine the conceptual model by testing sensitivity to semi-confined conditions, unconfined conditions, aquifer boundaries, and aquifer morphology. The outcomes would then be used to inform how the detailed numerical model should be structured.
2. The north-east boundary where it represents the Colac-Birregurra fault be constructed in the numerical model to allow for flux across the fault. Initial settings during model calibration should allow for no resistance to flow, and then reduced until a satisfactory calibration is obtained. An alternative approach would be to include a zone of low transmissivity aquifer on the north side of the fault and include observation bores 56055 and 69497 for model calibration.
3. Consideration be given to obtaining groundwater level data from private bores 50057 and 50061 (which are in close proximity to observation bore 50056) to better determine current groundwater level on the north side of the Colac-Birregurra fault. This would significantly reduce uncertainty regarding drawdown transmission across the fault. If historical data could also be found then this could be analysed using methods similar to those applied in this assessment to evaluate the degree of transmissivity reduction across the fault.
4. The conceptual model be reviewed in the regions not included in this report where the current groundwater model has poor calibration.
    a. The review to be undertaken using the same approach used in this assessment.
    b. Before the review is undertaken there should be a check that all available observation bores with long term records are being used for model calibration. Drawdown for observation bore sites that were not used for model calibration should be extracted from the model and used to refine/identify areas where the numerical model has poor calibration.
    c. Develop a simple numerical model to assist with refining the conceptual model, or simplify the existing model (as per recommendation 1)
5. Gamma logging existing bores be undertaken to provide high quality information on aquifer and aquitard lithology.
6. Leakage across the Bambra Fault be evaluated using the same methods used in this report
7. Consideration be given to undertake the pumping test that was proposed as part of the Newlingrook groundwater investigation to assess hydraulic connection between the unconfined and confined section of the aquifer across the Bambra Fault.

7 References

Jiao and Zheng (1997): The Different Characteristics of Aquifer Parameters and their Implications on Pumping-Test Analysis. Ground Water Vol. 35, No. I, p25 – 29

Witebsky, S., Jayatilaka, C., and Shugg, A. (1995): Groundwater Development Options and Environmental Impacts. Barwon Downs Graben, South Western Victoria. DNRE